Application of dendroclimatic methods in assessment of climate change impacts on the annual growth of Schrenk spruce in the Ile River basin, southeastern Kazakhstan

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Abstract

Forests are very important for people's livelihood. They provide important ecosystem services and goods. However there are many threats that interfere with the normal functioning and development of forest ecosystems. In the last decades, the climate change problem has become particularly prominent. Climate change strongly affects forests growth and regeneration and can lead to such effects as redistribution of climatic drivers of tree growth, changes in vegetation periods and species composition, increasing mortality and shifting of tree lines. The influence of climate change processes on functioning and dynamics of forests in Kazakhstan is understudied, and is observed in the relatively small number of dendroclimatic studies. Additional limitations in understanding of climate-growth relationships arise from insufficient spatial and temporal coverage of those studies and the absence of a qualitative analysis of already available information for identification of common patterns and differences in the impacts of tree growth on climate. The main research goal of this thesis was accordingly to address these limitations. An analysis of all available publications on dendroclimatic studies in Kazakhstan was performed. This analysis not only summarized the available information on climate-growth relationships, but also provided certain information about existed research gaps. Some of those gaps were addressed by an investigation of variation of climate-growth relationships of Schrenk spruce in the Ile River basin. The study revealed certain differences in reaction of earlywood, latewood and total ring width on climate in four mountain ranges of the Ile River basin. The strong influence of climate change was observed in a decreasing temperature signal around the 1970s. Revealed periodicities in the fluctuation of tree-ring indices suggested an influence of certain climate indices such as North Atlantic Oscillation and the Tropospheric Biennial Oscillations. Collectively, the analysis in this dissertation contributes to development of the tree-ting network of Kazakhstan. Obtained information should help in assessment of possible impacts of climate change on Schrenk spruce forests in Kazakhstan.

Zusammenfassung

Wälder stellen wichtige Ökosystemleistungen und -güter bereit und tragen damit maßgeblich zur Lebensgrundlage der Menschen bei. Sie unterliegen jedoch vielseitigen Bedrohungen, welche die volle Funktionsfähigkeit des Ökosystems gefährden und deren Entwicklung beeinträchtigen. In den letzten Jahrzehnten sind es vor allem die durch den Klimawandel hervorgerufenen Probleme, die zur Gefährdung der Waldökosysteme führen. Diese wirken sich stark auf Änderungen der Vegetationsperiode, der Artenzusammensetzung, der Zunahme der Sterblichkeit, der Verschiebung alpiner Baumgrenzen und insbesondere auf das Wachstum und die Regeneration der Wälder aus, was wiederum zu einer Umverteilung der Klimatreiber beiträgt. Inwiefern sich diese auf die Funktionsweise und die Walddynamik in Kasachstan äußert, ist aufgrund der wenigen durchgeführten dendroklimatischen Untersuchungen im Detail unklar. Hinzu kommt, dass für die qualitative Bewertung der Klima-Wachstums-Beziehungen diese Studien in ihrer räumlichen und zeitlichen Abdeckung unzureichend sind. Zu den bereits verfügbaren Informationen fehlen zur Einschätzung gemeinsamer Muster und Unterschiede hinsichtlich der Reaktion des Baumwachstums auf das Klima qualitative Analysen. Der Schwerpunkt dieser Arbeit liegt somit darin, für diese Themenfelder einen forschungsrelevanten Beitrag zu leisten. Hierfür wurden alle verfügbaren Publikationen zu den dendroklimatischen Untersuchungen in Kasachstan analysiert. Diese Analyse ermöglichte nicht nur die Zusammenfassung der verfügbaren Informationen zu den Beziehungen zwischen Klima und Wachstum, sondern lieferte zudem konkrete Informationen zu vorhandenen Forschungslücken. Einige dieser Lücken wurden durch die Untersuchungen der variierenden Klima-Wachstums-Beziehungen der Schrenks Fichte (*Picea schrenkiana*) im Einzugsgebiet des Ile-Flusses geschlossen. Die in vier Gebirgszügen des Ile-Beckens durchgeführte Studie verdeutlicht unterschiedliche Reaktion von Früh-, Spätholz und Gesamtringbreite auf den Klimawandel. Der starke Einfluss des Klimawandels wurde durch die Abnahme des Temperatursignals um die 1970er-Jahre beobachtet. Eine erkennbare Periodizität bei Schwankungen der Baumringindizes lassen auf einen Einfluss bestimmter Klimaindizes, wie beispielsweise die Nordatlantische Oszillation, die Tropospheric Biennial Oscillations usw. Die im Rahmen dieser Dissertation durchgeführten Untersuchungen tragen zur Entwicklung eines Baumring-Netzwerkes in Kasachstan bei. Die erhoben Daten sind für die Bewertung möglicher Auswirkungen des Klimawandels auf die Wälder der Schrenks Fichte in Kasachstan hilfreich.

Contents

List of Figures

List of Tables

List of Supplementary Material

Figures SM

Tables SM

Chapter I:
Introduction

1 Background

1.1 Tree growth and climate

Climate is one of the main factors affecting tree growth. The science that studies relationship between tree growth and climate is called dendroclimatology. Methods used in dendroclimatology help investigators to study the interconnection between climate and the functioning, dynamics and productivity of forest ecosystems by analyzing tree-ring growth (Schweingruber, 1996; Speer, 2010). Additionally, dendroclimatology provides information for understanding the variability in past and present climate through climatic reconstructions (Fritts, 1971; Bitvinskas, 1974; Shiyatov, 1986). In terms of paleoclimatic studies, tree rings have proved to be a very reliable source of information which is especially valuable in areas where meteorological observations were not constant or not carried out at all (Esper et al., 2002; Cook et al., 2004; Büntgen et al., 2011). Tree rings can provide climatic information for periods long before the onset of instrumental observations, with yearly resolution (Lara and Villalba, 1993; Büntgen et al., 2005). Investigations of climate-growth relationships help to predict how climatic changes could affect growth and regeneration of forests, which is especially important for forest management and for biodiversity conservation (Payette et al., 1989; Cook and Cole, 1991; D'Arrigo and Jacoby, 1993).

A large number of studies have already indicated significant changes in climate-growth relationships all over the world. For example, a number of studies revealed such effects as the redistribution of climatic drivers of tree growth, changes in vegetation periods and increasing of variability of tree-growth (Briffa et al., 1998; Walther et al., 2002; Andreu et al., 2007; Babst et al., 2019). These effects in turn can affect species composition, creating favorable conditions for one species and increasing mortality of another, or for instance lead to the shifting of upper and lower tree lines (Payette et al., 1985; Grace et al., 2002; Aitken et al., 2008; Allen et al., 2010). Other effects include increasing ring widths due to the fertilizing effects of increasing atmospheric CO2 concentration and enhanced evapotranspiration, or reduction of photosynthesis due to increase in strength and frequency of drought (LaMarche et al., 1984; Yin et al., 2008; Lévesque et al., 2013).

Strong climatic changes increase the negative influence of other threats, such as fires, extreme weather events, insect and pathogen outbreaks, etc. (Dale et al., 2001). For example in the beginning of the 21st century 5-15 million hectares burned annually in boreal forests, primarily in Siberia, Canada and Alaska, and there is a big awareness of vulnerability of forests in this region with respect to climate change (Flannigan et al., 2006). In turn, losses of timber caused by pests could be even higher. For example, in the boreal zone of Canada it can be as much as 1.3-2.0 times the mean annual losses due to fires (Volney and Fleming, 2000). Climate warming can lead to expansion of pests to new territories and also to an increase of the effective duration of local outbreaks (Jepsen et al., 2008). Finally, increasing of intensity and frequency of extreme weather events (Goswami et al., 2006; Cai et al., 2014) can cause direct damage through branch breaking, trunk breakage, or complete stand destruction. For example in 2005 hurricane Gurdun damaged over 60 million m3 of timber in Sweden (Kirilenko and Sedjo, 2007).

However, the strength of these changes also depends on a number of factors. While in some parts of the world we observe a strong negative effect, in other parts it could be barely noticeable or even positive (Kirschbaum, 2000; Chazdon, 2008; Lindner et al., 2010). Of great importance are the measures taken by countries for mitigation and adaptation to changes. Further, such factors as sensitivity of certain tree species to climate change and the total area covered by forests play an important role. Here we also can mention for example humidification conditions, orography or the age of trees. Therefore we see that effect of climate change on forests varies considerably from one region to another (Carrer and Urbinati, 2004; Chen et al., 2010; Way and Oren, 2010). In these terms, regions like Central Asia are of particular importance because they are projected to exhibit an amplified climatic response (Seddon et al., 2016). This is connected with accelerated warming. The average rate of warming in the region is 0.39°C/10a for period from 1979 to 2011 which is higher than the mean rate for global land areas (Hu et al., 2014). Temperature is further projected to increase 1-2 °C by 2030-2050, accompanied by an increase of aridity across the entire Central Asia and especially in Kazakhstan, Uzbekistan and Turkmenistan (Lioubimtseva et al., 2005; Lioubimtseva and Henebry, 2009). In the Central Asia as a whole, climate change induced threats are also complemented by such destructive phenomena as overgrazing, overharvesting and forest degradation from excessive recreation use, which brings additional pressures and interfere with natural forest renewal (Kushlin et al., 2003).

The area of forests in Central Asia is relatively small compared to the total area and is equal to around 12 million hectares (www.fao.org). However, forests are very important for people’s livelihood. They play an important role in water-protection and water-regulation, prevention of soil erosion, the carbon cycle and agricultural land productivity (Pimentel et al., 1992; Breshears et al., 2003; Luyssaert et al., 2008). Forests are a habitat for many unique plant and animal species, which also provide clean air and water, making a vital contribution to both people and the planet (FAO, 2018).

1.2 Forests of Kazakhstan as a study region

Despite the great importance of forest resources, no systematic forest management existed in Kazakhstan until the mid of the 20th century (Meshkov et al., 2009). During the last decades, the situation has started to improve thanks to support from international organizations such as the World Bank. Currently, control over forest resources is exercised by the Forestry and Wildlife Committee, which is a part of the Ministry of Agriculture of Kazakhstan. Kazakhstan ratified the Kyoto Protocol, Aarhus Convention and Convention on Biological Diversity, became a party of the United Nations Framework Convention on Climate Change and implemented activities targeted to improve environmental impact assessment systems with a goal of a transition to a “green” economy (Kushlin et al., 2003; Sehring, 2012). The importance of effective natural resource management was also noted in the national strategy “Kazakhstan – 2050” (https://strategy2050.kz/en/multilanguage/). Several big forest mitigation measures were suggested by Kazakhstan’s National Climate Change Action Plan in regards to climate change problem. These include providing financial incentives for new afforestation activities on private lands, encouraging agroforestry activities to contribute to sustainable development, and promoting improved legal and policy frameworks to control deforestation (Yesserkepova, 2010).

Systematic dendrochroclimatic studies could help to fulfill these programs and commitments made by the country under ratified conventions. Unfortunately, even today dendroclimatic studies in Kazakhstan are not carried out on a regular basis. Meanwhile there is a good potential for such studies, especially along the northern and southern perimeters of the country where the majority of forests grow. In total, the flora of Kazakhstan includes 68 species of trees, many of which are widely used in dendroclimatic studies all over the world, for example: Pinus sylvestris L, Betula pendula, Larix sibirica or Picea schrenkiana Fisch. et Mey (Zhantlessova and Zhumadina, 2014; Zhantlessova, 2015b).

The total area of forests in Kazakhstan is around 3.3 million hectares (areas covered by closed forest), excluding areas with Saxaul (*Haloxylon* spp.) trees/stands (thickets) and bushes/brushwood) (http://www.fao.org/3/a-az250e.pdf). It consists of several domains, which are separated from each other by vast areas of steppes, deserts and semideserts and include: Altay Mountains, Tian Shan Mountains, northern forest-steppe, riparian forest along major rivers and agricultural shelterbelts (Kushlin et al., 2003).

Forests of the Ile River basin

The majority of Kazakhstan's forests are located in the southeastern part of the country, in particularly in the Ile River basin and the largest number of dendroclimatic studies was also conducted here. The dominant tree species here is the Schrenk spruce (*Picea schrenkiana* Fisch. et Mey) which covers the slopes of surrounding Tian Shan Mountains. Other species growing in this area include for example: maple (Acer semenovii), aspen (Populus tremula), birch (Betula pendula), and juniper (Juniperus pseudosabina). Forests of the Ile river basin belong to the Dzungar-North Tien Shan group of vegetation altitudinal zonality types, which consist of five belts and sub-belts of vegetation types, including: steppes, dark coniferous forests and meadows, subalpine-like meadows and juniper elfin woods, cryophytic (alpine-like) meadows and communities of Kobresia and the subnival belt (Akzhygitova et al., 2003). Forest territories are mainly located within 4 national parks and therefore their use is strictly limited to recreational and scientific needs.

The first dendroclimatic studies here began in 1970s (Grigorieva and Suslov, 1972) and were relatively active until the collapse of the Soviet Union. After that, studies stopped for almost 20 years and resumed with research by Passmore et al. (2004). In the last 5 years, rather high activity of dendroclimatic studies was observed in the region. In particular, a number of studies on climate reconstruction have been published (Chen et al., 2017; Zhang et al., 2017a; Zhang et al., 2017b; Panyushkina et al., 2017). However despite the increased research activity, some research gaps still remained. These gaps include, for example, relatively small temporal and spatial coverage as well as the analysis of changes in climate-growth relationships due to recent climate changes.

In addition to the direct impact of climate change, a large influence is also attributed to indirect factors such as extreme weather events, landslides, avalanches, mudflows and earthquakes. For example, in 2011 windstorms damaged 480 hectares of forest plantations in the Ile Alatau Mountains (Sagitov et al., 2016). Additionally, this damage could be amplified later by subsequent increase of populations of pests (Mukhamadiev et al., 2014). Investigations of the influence of such extreme events are very important because they improve our understanding of climate-growth relationships in the region.

2 Conceptual framework

2.1 Research questions and objectives

The main goal of this dissertation is to better understand climate-growth relationships of Schrenk spruce in the Ile River basin and possible changes in these relationships due to climate change by (1) analyzing available and collecting new data on climate-growth relationships of Schrenk spruce in the region and (2) assessing possible changes and differences in reaction of Schrenk spruce growth due to climate change process in the region.

By achieving this goal, the dissertation contributes to development of the tree-ring network of Kazakhstan, better understanding the interconnections between climate and Schrenk spruce growth, and provides potentially important information for local policy-makers and authorities to restructure and improve forest conservation and forest resource management strategies. To achieve these goals, this dissertation addresses two main research questions:

Research Question I: *What do we know about climate-growth relationships of Schrenk spruce in Kazakhstan?*

Information on climate-growth relationships of Schrenk spruce in Kazakhstan is quite small, which is a result of the relatively small number of conducted dendroclimatic studies. Moreover, the available information is not systematized, which limits the understanding of the general patterns and certain spatiotemporal features. Additionally, some publications indicate that dendroclimatic studies in Kazakhstan started during the times of the Soviet Union. Hence, there may be certain rare publication which could also provide important dendroclimatic information.

Research Question II: *How does the response of Schrenk spruce growth on climate variation in the Ile River basin vary spatially and temporally, and how is it associated with climate change?*

The climate-growth relationships are influenced by different factors such as orography, age of trees, soil characteristics, etc. Therefore, even at relatively small scales, reactions of tree growth on climate can vary quite a lot. Understanding these variations is very important for assessing and forecasting possible changes in productivity and dynamics of forest ecosystems due to climate change.

Two main objectives were set to answer these research questions:

Objective 1. Analyze all available information on dendroclimatic studies in Kazakhstan.

A qualitative literature analysis was conducted to help us understand basic climate-growth relationships of Schrenk spruce and other tree species in Kazakhstan. It is also provided information on certain features, differences and similarities in reaction of tree growth on climate, and additionally revealed existing research gaps.

Objective 2. Assess changes in climate-growth relationships of Schrenk spruce in the Ile River basin.

Using the results obtained from Objective 1, we were able to define which data need to be collected in order to improve our understanding of the interconnections between climate and Schrenk spruce growth in the Ile River basin.

2.2 Structure of this thesis

This thesis consist of five chapters: The introduction (Chapter I) is followed by three core chapters (Chapters II-IV) that contribute to answering the research questions, and a synthesis chapter (Chapter V) that provides a summary of the core chapters, demonstrates interconnections between them, and provides an outlook for potential future research. The three core chapters were written as stand-alone manuscripts and are either published in or submitted to international, peer-reviewed journals. Since each of core chapters needed to meet the required structure for journal articles, a thematic overlap between chapters has to be accounted for.

Chapter II ***Zubairov, B.****, Lentschke, J., Schröder, H., 2019. Dendroclimatology in Kazakhstan. Dendrochronologia 56, In progress.*

Chapter III ***Zubairov, B.****, Heußner, K.U., Schröder, H., 2018. Searching for the best correlation between climate and tree rings in the Trans-Ili Alatau, Kazakhstan. Dendrobiology 79, 119-130.*

Chapter IV ***Zubairov, B.****, Heußner, K.U., Lentschke, J., Schröder, H., (Submitted).* Variability of climate-growth relationships of Schrenk spruce (*Picea schrenkiana* Fisch. et Mey) in the Ile River basin (northern Tien Shan Mountains). *Regional Environmental Change.*

Chapter II:
Dendroclimatology in Kazakhstan

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Abstract

We have reviewed 43 studies related to dendroclimatology in Kazakhstan, and additionally 13 studies related to other subfields of dendrochronology, which have been published during the past 40 years. This review also includes studies published in Russian, Kazakh, German and Chinese languages, which are not easily accessible to international researchers.

Dendroclimatic studies in Kazakhstan began back in the days of the Soviet Union and were actively conducted in the southern and northern parts of the country. With the collapse of the Soviet Union dendroclimatic studies stopped and resumed only 15-20 years later. Within the last 5 years, the intensity and quality of dendroclimatic studies increased significantly. Several research groups have investigated climate-growth relationships of Scots pine, Silver birch, Siberian larch, Siever's apple and Schrenk spruce. Schrenk spruce was the most widely studied of these species, and several climatic reconstructions have been published based off their climate-growth relationships. Results of most studies on Schrenk spruce demonstrated good consistency, allowing the general patterns of climate-growth relationships to be accurately traced. Unfortunately, studies on other tree species have either lower level or represented just by one or two studies. It would therefore be premature to make any generalizations on these species at the current stage.

We conclude that there is a good potential and good base for continuing dendroclimatic studies in Kazakhstan. There is a need to close several research gaps which limit our knowledge, such as chronologies' length, application of new methods, species composition and spatial coverage. Closing these gaps let us significantly improve the dendrochronological network of Kazakhstan and provide important data for further hydrological and climate studies in Kazakhstan.

1 Introduction

Dendroclimatology is a subfield of dendrochronology which investigates variation in tree-ring structure in order to obtain information about past climate (Speer, 2010). As a climatic proxy tree rings proved to be a very reliable and valuable source of information (Fritts, 1976; Esper et al., 2002; Treydte et al., 2006; Cook et al., 2010; Büntgen et al., 2011). This source is especially relevant in such countries like Kazakhstan, where the network of meteorological stations is sparse and the period of observations is relatively short (Williams and Konovalov, 2008; Menne et al., 2012).

The Republic of Kazakhstan is the world's ninth largest country. Located in the middle of Eurasia continent, it has an area of 2724.9 mln. ha. Absolute elevation varies from -132 m a.s.l to 6995 m a.s.l. The relief is characterized by the predominance of plains and lowlands, though significant areas are occupied by hills and low mountains. High mountain areas are stretched along southern and eastern part of the country and occupy less than 10% of the territory of Kazakhstan (Iskakov and Medeu, 2007). In total more than a half of the territory (179.9 mln. ha.) is desertified (De Beurs and Henebry, 2004). The flora of Kazakhstan is rich and diverse: it includes 68 species of trees, 266 species of shrubs, 433 species of subshrubs, 2598 species of perennial plants and 849 species of annual plants (Zhantlessova, 2015b). Kazakhstan possesses significant forest resources (3.309 mln. ha.) (http://www.fao.org/faostat/en/#country/108), however distribution of forest cover across the territory is extremely uneven: 69.3% of forest cover is located along the southern perimeter of the country, while only 15.5% and 12.1% is located along the southeastern and northern perimeters of the country, respectively (Zhantlessova and Zhumadina, 2014; Zhantlessova, 2015b).

The climate conditions in Kazakhstan are characterized by frequent droughts and high continentality. Except for the high mountain areas, annual precipitation in most of the country is almost two times lower compared to potential evaporation (250-300 and 500-600 mm yr-1 respectively), which results in a severe moisture deficit for plants (Kushlin et al., 2003; Usoltsev and Vanclay, 1995). Drought risks are also amplified by the high rate of mean annual air temperature (MAAT) increase. For example, according to Pilifosova et al. (1997), over the period 1891-1990, it was almost two times higher than the global rate of increase.

The territory of Kazakhstan is primarily influenced by the Siberian air masses and westerlies that bring water vapor form the North Atlantic. The maximum mean temperature in January is -15°C with minimums of -40°C. The summers are hot and dry with the maximum mean temperature in July up to 40°C. The mean annual precipitation in the northern part of the country is around 250-350 mm while in the southern part it is 100-120 mm (Salnikov et al., 2015). Among important controlling factors which determine precipitation and drought conditions are El Niño – Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) (Gerlitz et al., 2016).

Despite there being a good potential for conducting all types of dendrochronological studies, it seems that the number and variety of studies performed in Kazakhstan are rather small. For example, in the International Tree-Ring Data Bank (ITRDB) (https://gis.ncdc.noaa.gov/maps/ncei/paleo), there is only one chronology for the entire territory of Kazakhstan. Meanwhile, it is well known that not all researchers upload their chronologies to the ITRDB and moreover, there might be some old publications which are difficult to access because of their rarity. Hence, it can be assumed that in reality the state of dendroclimatology in Kazakhstan is better than it seems at first glance.

Indeed, the primary analysis of the literature showed that even during last couple years the intensity of dendroclimatic studies was rather high (Chen et al., 2017; Kopabayeva et al., 2017a; Panyushkina et al., 2017; Panyushkina et al., 2018; Zhang et al., 2017a; Zubairov et al., 2018a). Additionally, some authors indicated that such studies began quite a long time ago, back in the days of the Soviet Union (Solomina et al., 2012; Panyushkina et al., 2018; Zubairov et al., 2018a; Zubairov et al., 2018b). These facts induced our interest for further investigation of the history of dendroclimatic studies in Kazakhstan, and also motivated us to try to form a consistent picture of the climate-growth relationship patterns, by synthesizing findings from all relevant publications.

The structure of the paper is organized as follows. In section 2 we briefly reviewing dendroclimatic studies in Kazakhstan. In section 3 we present a pivot table of the main findings and briefly summarize conclusions presented in publications. In section 4, additionally to dendroclimatic studies we reviewed studies related to other subfields of dendrochronology. We conclude this review with a short discussion of the state of knowledge and remaining research gaps in section 5.

2 History

Dendroclimatic studies in Kazakhstan can be conditionally divided in two periods, before and after the collapse of the Soviet Union around 1990. Between these two periods there was a 15-20 years gap when dendroclimatic studies were not conducted. Additionally, the absolute majority of studies were focused on two tree species, Schrenk spruce in the South and Scots pine in the North (Figure II–1).

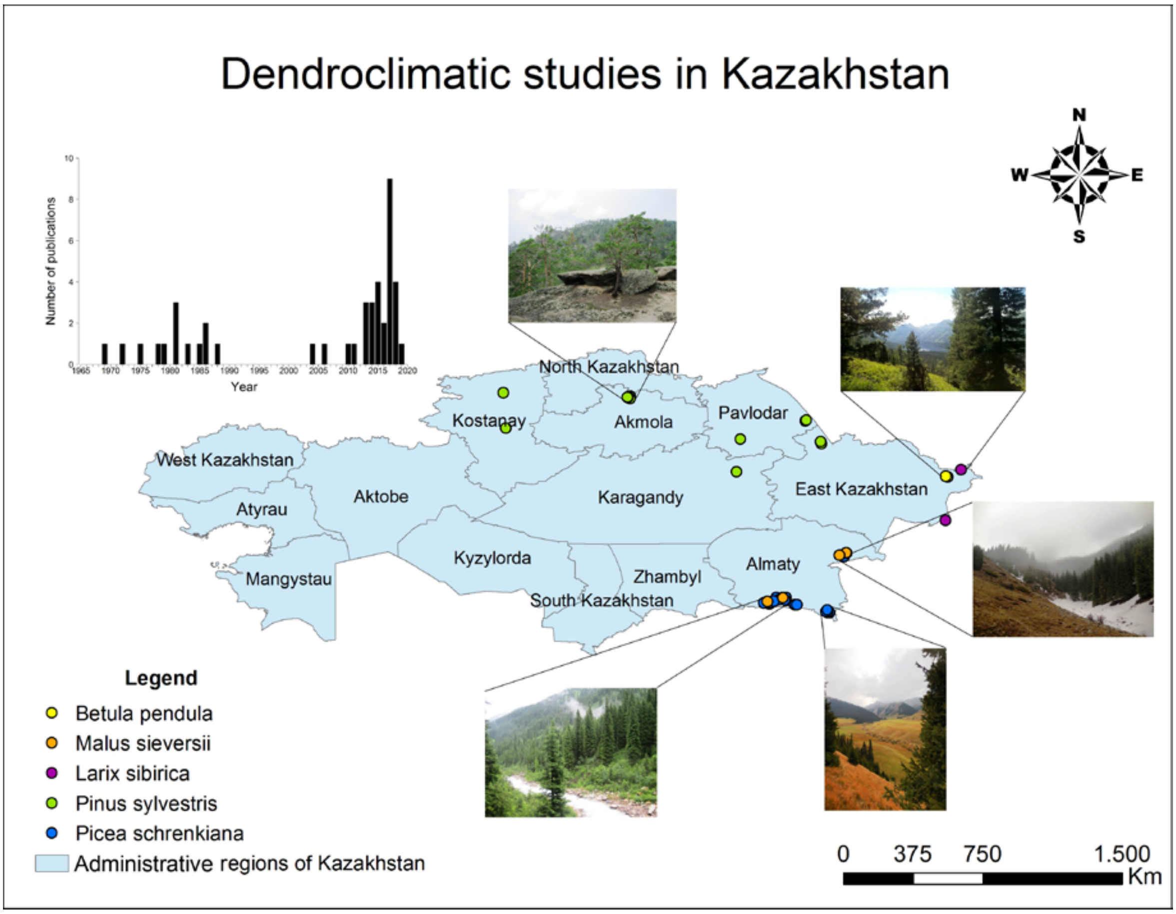

Figure II-1: A map of dendroclimatic studies in Kazakhstan with photos representing the typical landscape at the sampling sites (Photos by authors). Dot color indicates tree species used, in and the bar chart shows the number of publications related to dendroclimatology by year.

2.1 Dendroclimatology before the fall of the USSR

The first attempts to understand how the radial growth of trees is affected by the climatic factors, began in early 1970s, when Komin and Pugachev investigated annual growth rate of Scots pine (Pinus sylvestris L.) in pineries of the Kostanay region in northern Kazakhstan (Komin, 1969; Pugachev, 1975). Authors revealed certain periodicities in the tree-ring indices (TRI) fluctuations and showed that radial growth of trees is strongly affected by the solar activity and precipitation regime. Later on, these conclusions were supported and supplemented by new studies (Grigorieva et al., 1979; Olenin and Gurskyi, 1985; Pugachev, 1986; Olenin and Mazepa, 1988). Results presented in Olenin and Gurskyi (1985) and Olenin and Mazepa (1988) provided new information on periodicities in tree-ring growth. The authors additionally made a forecast of tree growth until 2010 expecting a significant decrease in growth rate of Scots pine, especially in dry forests, showing that growth rate of Scots pine in northern Kazakhstan is highly dependent on the moisture level. A similar prognosis was made by Pugachev (1986) who also pointed to the probability of decrease of pine growth especially during the periods 1982-1990, 1995-2000, 2005-2009 and 2014-2018. Of particular interest was the article by Grigorieva et al. (1979), as this was the first attempt to investigate drought occurrence by using dendroclimatology in Kazakhstan. The authors managed to reconstruct a hydrothermal coefficient (HC) by Selyaninov (1958), which is described by the following formula:

$$HC = \sum r / 0.1 \sum t \qquad \text{Equation 1}$$

where $\sum r$ is a monthly sum of precipitation, and $\sum t$ is a sum of temperatures for the same month. The reconstruction let them to detect periods of especially strong droughts, and to predict drought probability in the first half of the 1980s. Moreover, it was shown that the onset of drought in Akmola region is closely related to the minimums of solar activity.

In the same period of time but in the opposite end of the country, intensive studies on Schrenk spruce (Picea schrenkiana Fisch. et Mey) were conducted. They began almost simultaneously with studies in the North and first results were published in the beginning of the 1970s. Grigorieva and Suslov investigated fluctuations of tree-ring growth of Schrenk spruce in the Ile Alatau Mountains (formerly known as Transili or Zailiyskiy Alatau). Using the obtained information, they revealed certain periodicities in the TRI and made a forecast of spruce growth, expecting an intensive growth in 1973 and a sharp decline after that, which was predicted to reach a minimum in 1987-1988 (Grigorieva and Suslov, 1972). Later these results were confirmed and supplemented by Borscheva, who also conducted studies in the same region and published a number of very important and thorough works (Borscheva, 1983). Based on at least 90 cross sections and 830 cores from 670 spruce trees collected at altitudes ranging from the lower to the upper tree limits and across three mountain ranges (the Ile Alatau, the Kungey Alatau and the Terskey Alatau), she investigated relationships between tree-ring growth and different climatic, biological and ecological factors. One of her first observations was that variations in the mean sensitivity (MS) coefficient of Schrenk spruce is directly connected to latewood (LW) proportion, the higher the proportion, the higher the coefficient's value. This coefficient in general varied from 0.15 to 0.27. However, it was found to be higher in some cases, for example when trees grow in harsh conditions with the lack of nutrients, water and sunlight, or if they grow on territories with permafrost. The MS was also affected by the age of trees; in general old trees had higher MS compared to young trees. It was getting higher from the Ile Alatau in the west to the Terskey Alatau in the east, which was explained by a reduction in the amount of precipitation in this direction. This in turn suggested that precipitation is a principal climatic factor affecting Schrenk spruce growth. However, in some cases, for example in deep and narrow gorges, the influence of precipitation is weakened due to factors such as exposition and orography, where the temperature then becomes the more significant climatic factor (Borscheva, 1981a; Borscheva, 1981b; Borscheva, 1981c; Borscheva, 1981d; Borscheva, 1983; Borscheva, 1986).

According to Borscheva, climatic conditions of the previous vegetation year also have some influence on Schrenk spruce growth, mainly affecting annual variability of radial growth through the formation of vegetative buds and needles (Borscheva, 1983). Her correlation analyses demonstrated that fluctuations of earlywood (EW) and total ring width (TRW) indices are mainly determined by precipitation during the previous autumn – current spring period. She also mentioned that time period and strength of this limiting factor depends on the place of tree growth. For example the duration of lack of moisture is shorter at low and high elevations (from 1400 to 2000 and from 2500 to 2900 m a.s.l.) and longer at mean elevations (from 2000 to 2500 m a.s.l.). It is also shorter in the Ile Alatau (6-8 months from September-October to January-February) and longer in the Terskey Alatau and in the Kungey Alatau (8-10 months from September-October to April-May). This was explained by the presence of high mountains, which hold the precipitation brought by northwestern air masses (Borscheva, 1983). The most significant results obtained by Borcsheva include three climatic reconstructions: a 318 year reconstruction of precipitation for the Terskey Alatau, a 196 year reconstruction of precipitation for the Ile Alatau, and a 217 year reconstruction of temperature for the Kungey Alatau (Borscheva, 1983). Finally, based on extrapolation of revealed dominant periodicities, Borscheva made a forecast of climate conditions in the Ile Alatau Mountains to 2006. According to this forecast, she expected a decrease of autumn-winter precipitation in the period from 1982 to 1985, after which precipitation would increase gradually, reaching the maximum in 2005-2006. In turn, increasing of humidification during summer periods was predicted to start in

1983-1985 and last up to 1989-1990. After that, Borscheva expected a decrease in precipitation until 2004-2005 (Borscheva, 1983).

The juniper is another species which was used in dendroclimatic studies in southern Kazakhstan. It is quite widespread in the northern Tian Shan, especially species such as Juniperus turkestanica Kom., Juniperus pseudosabina Fisch. et Mey and Juniperus sabina L. However, in Kazakhstan it was much less investigated compared to Schrenk spruce. Only two publications describing studies on juniper in Kazakhstan were found in available sources. The first one is dedicated to investigation of fluctuations of growth of Juniperus turkestanica Kom. in the Ile Alatau Mountains (Borscheva, 1978), and the second one described climate-growth relationships of juniper (Mukhamedshin and Sartbayev, 1981). Unfortunately, the second publication only indicated that some of the samples were collected within the territory of Kazakhstan, but it was not clear how many samples and where exactly. Nevertheless, the authors made several interesting conclusions. In particular they found an interconnection between the activation of the fruiting of juniper and maximums of solar activity. During the observation period from 1956 to 1973 these two events coincided twice, in 1957 and in 1968. It was also revealed that precipitation is the main limiting factor of growth at low and mean elevations. Meanwhile, high temperatures during the vegetation period, and especially in July, cause a negative influence on growth. At high elevations where climate is colder and more humid, the influence of precipitation becomes weaker and the main limiting factor here is temperature, especially temperature conditions in June and July. An interesting fact noticed by Mukhamedshin and Sartbayev was that different species of juniper have different reactions to climate conditions in summer. It appeared that hot and dry summers positively affect growth of Juniperus zeravchanica Kom. and Juniperus semiglobosa Reg. and adversely affects growth of Juniperus turkestanica Kom. The authors also revealed certain periodicities in fluctuations of climatic conditions in Kazakhstan (Mukhamedshin and Sartbayev, 1981).

2.2 Dendroclimatology after the fall of the USSR

The second period of dendroclimatic studies in Kazakhstan started in 2004 in the Ile Alatau Mountains, when Passmore et al. in the framework of geomorphological studies investigated basic climate-growth relationships of Schrenk spruce (Passmore et al., 2004). The authors collected samples from three sites in the height range from 1500 to 3000 m a.s.l. Correlation analysis showed that temperature is the principal factor affecting Schrenk spruce growth. Obtained results indicated that warming in the study area has been in progress since the 1870’s with exceptional increase marked after 1920. Within this warming trend, there were three cooler intervals illustrated by the 11-year moving average of the master plot ring widths. The authors also noted an increase in the variance of tree-ring widths, which in turn suggested an increase in seasonal variability. It was shown that annual growth variations were relatively suppressed in the period from 1750 to 1870. After that, variability gradually increased, showing marked low to high oscillations over ~ 5 to 10-year time intervals. Obtained information was applied for understanding of spatial and temporal patterns of potentially hazardous land forming processes such as debris flow (Passmore et al., 2004). Two years later Jurina et al. published a paper where the authors investigated possibilities and restrictions of climate and glacier mass balance reconstructions using Schrenk spruce (Jurina et al., 2006). According to presented results, such studies have a good potential. Correlation analysis showed that EW growth indices correlate positively with October-April precipitation and negatively with seven years averaged April-August mean temperature. Additionally the authors indicated that tree-ring growth probably depends on precipitation during the entire year and not only from October to May as Borscheva assumed. However, revealed climate-growth relationships have some features. First of all, correlation analysis showed instability of the temperature signal especially during particularly cold and warm periods. Second, there were some difficulties in testing of precipitation signal due to the short observation period in high mountain areas. Analysis of the Tsentralniy Tuyuksuyskiy glacier mass balance data showed that EW of Schrenk spruce correlated positively with accumulation and negatively with ablation. Nevertheless, despite correlation values being statistically significant, the difficulties with testing of climate-growth relationship described above imposed certain restrictions on the possibility of glacier mass balance reconstruction (Jurina et al., 2006). In 2010 a new manuscript was published. In this work climate-growth relationships of Schrenk spruce were investigated in the framework of archeological studies in the Ile Alatau Mountains (Panyushkina et al., 2010). Based on obtained results, the authors suggested a 300-m change in the vertical gradient of closed-canopy spruce forests in the study region since ca. 3500 years ago. The authors linked such changes both to more pristine conditions of mountain ecosystems and a wetter climate. Correlation analysis showed that tree growth is positively impacted by May precipitation and August monthly temperature. This relationship was explained in the context of moisture stress caused by increased evaporation in the beginning of the growing season. Of particular interest was the use of daily climate data for correlation analysis, which provided not only higher correlation values but also more precise time intervals. Probably the most interesting and important question raised for future dendroclimatic studies, was the investigation of the potential of the archeological wood for climatic reconstruction. Analysis revealed a strong climatic signal in the archeological tree-ring record. However, there were several issues which complicate interpretation of the signals, for example the origins of archeological wood and variability in climatic responses. The authors were therefore rather cautious in assessing the viability of such studies (Panyushkina et al., 2010). The next manuscript which should be mentioned is the one published by PAGES 2k Consortium (2013). This was a very big study of temperature changes during the past two millennia. The data set used in this work also included Schrenk spruce chronology built on samples collected in the Ile Alatau Mountains. This is the only tree-ring chronology on the ITRDB for the territory of Kazakhstan. Unfortunately, the design of the study does not allow deriving information on climate-growth relationships just for Kazakhstan.

The intensity of dendroclimatic studies on Schrenk spruce has risen significantly during last three years. Three studies were published in 2017. The first publication was by Chen et al. (2017) and presented a reconstruction of the mean August-January Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) since CE 1785 in the Ile Alatau. The second, by Zhang et al. (2017a), presented a 246-year reconstruction of June-May precipitation, also in the Ile Alatau. The third study, by Zhang et al. (2017b), presented a 189-year reconstruction of the self-calibrating Palmer Drought Severity Index (scPDSI) (Wells et al., 2004) from the previous July to current June in the Zhetysu Alatau (former name Dzungarian Alatau). Results presented in these three publications were in agreement with the results obtained in earlier studies and confirmed that main limiting factor of Schrenk spruce growth is moisture variation. The authors also investigated and analyzed periodicities of the reconstructed series. The analysis revealed interannual periodicities of 2-4 years which authors associated with the ENSO (Allan et al., 1996), the tropical biennial oscillation (TBO) (Meehl 1987) and NAO (Telesca et al., 2013). Additionally, an 11-year cycle was linked with solar activity and a 60-year quasi-periodicity was linked with the NAO. According to the authors, these results implied an influence of the large-scale land-atmosphere-ocean circulations (Chen et al., 2017; Zhang et al., 2017a; Zhang et al., 2017b). The last study by Zhang et al. (2017b) is of particular interest as their study area had not been studied previously, and they compared their findings directly with previous findings in the Ile Alatau. The comparative analysis revealed common signals in the variation of dry/wet periods and occurrence of extreme dry years. In turn, the occurrence of extreme wet years and number of dry years were different (Zhang et al., 2017b).

Four new studies on the Schrenk spruce were published in 2018. The first study presented a first reconstruction of runoff variation in Lake Balkhash Basin for period 1779-2015 (Panyushkina et al., 2018). In this study, Schrenk spruce samples collected from the eleven sites in the Ile Alatau Mountains were used for the reconstruction of October-September discharge of the Ile River. The second paper by Zhang et al. (2018) presented a 167-year July-October reconstruction of normalized differential vegetation index (NDVI) (Pettorelli et al., 2005), based on 93 Schrenk spruce samples collected from three sampling sites in the Ile Alatau Mountains. The third study published by Zubairov et al. (2018a) presented a 183-year precipitation reconstruction in the Terskey Alatau and the last one also published by Zubairov et al. (2018b) presented results on climate-growth correlations analysis between different tree-ring parameters, climate datasets and age groups of trees. The results of climate-growth correlation analysis of these four studies again confirmed the strong influence of summer temperatures and autumn-spring precipitation on Schrenk spruce growth. The main results of the presented studies include: variability and extremes of the Ile river discharge including climatic indexes and atmospheric circulation anomalies which have influence on these processes (Panyushkina et al. 2018), variations in vegetation coverage in the Ile Alatau (Zhang et al. 2018), variation in precipitation in the Terskey Alatau (Zubairov et al. 2018a) and combinations of various datasets which provide best climate-growth correlation results (Zubairov et al., 2018b). The last published study on Schrenk spruce is the one by Zhang et al. (2019). In this study the authors presented a 166-year reconstruction of annual glacier mass balance of the Tsentralniy Tuyuksu glacier based on samples collected from two sites in the Ile Alatau Mountains. It seems that difficulties of glacier mass balance reconstruction, described by Jurina et al. (2006), were solved by application of stable carbon isotope data analysis. The results of climate-growth relationship analysis are consistent with previous studies, indicating that the main limiting factor of growth is moisture variation in previous and current growing seasons. The mass balance changes of the Tsentralniy Tuyuksuyskiy glacier are driven by both temperature and precipitation. However, according to presented results, the glacier in general is more sensitive to temperature changes rather than changes in precipitation (Zhang et al., 2019). The lowest mass balance occurred in the 1910s; and the only decade with a positive mass balance was in the 1960s. Applying a 20-year low-pass filtering to the reconstruction authors also obtained information on variation of annual mass balance trends, which changed 6 times during the reconstructed period. Additionally, starting from 1968 the Tsentralniy Tuyuksuyskiy glacier has experienced the most intensive and longest period of melting in the past 166 years (Zhang et al., 2019). These results are consistent with glaciological studies which revealed a warming trend in Central Asia and increase of summer temperatures starting from 1970s (Aizen et al., 2006; Sorg et al., 2012). They also in agreement with results presented by Solomina et al. (2006), who reconstructed summer air temperatures and mass balances of several glaciers, including the Tsentralniy Tuyuksuyskiy glacier based on Schrenk spruce samples. In particular, results showed coincidences over periods of positive mass balance in 1881-1909 and 1951-1977. Unfortunately, the study by Solomina et al. was conducted on the territory of Kyrgyzstan and therefore not fully taken into account in this review.

Meanwhile in northern Kazakhstan studies on Scots pine have also resumed. A number of small studies were conducted in pineries of Akmola, Karagandy, Pavlodar and East Kazakhstan regions. Results presented in these studies provided general information on climate-growth relationships of Scots pine in northern Kazakhstan and they were in good agreement with results presented in earlier studies, indicating that the main limiting factor of growth is the May-June hydro-thermal conditions (Karnauhova et al., 2016; Karnauhova et al., 2018; Mapitov and Zhumadina, 2016; Mapitov and Zhumadina, 2017; Zhumadina and Mapitov, 2017). Additionally, some studies revealed a positive influence of high precipitation levels and high temperatures during autumn-winter season (Kopabayeva et al., 2017a; Kopabayeva et al., 2017b). Several studies also provided new information on periodicities and extreme years detected in the TRI fluctuations (Grigoriev and Karnauhova, 2013; Grigoriev and Karnauhova, 2014; Karnauhova et al., 2014a; Karnauhova et al., 2014b; Kopabayeva et al., 2017a; Kopabayeva et al., 2017b; Karnauhova et al., 2017).

Apart from studies on spruce and pine, several studies on other tree species were published. We found two studies on Larix sibirica, one by Shang et al., (2011) which presented a 310-year mean June temperature reconstruction based on samples collected in the Altai Mountains, and a second one by Dulamsuren et al., (2013) who presented an investigation on climate-growth relationships based on samples collected in the Saur Mountains, eastern Kazakhstan. Both studies indicated that summer temperature (in particular June-July) is the main limiting factor of growth. However the influence of this factor was found to be different in the study by Shang et al. (2011), where it was positive and strongest correlations were found for the current June.

Conversely, Dulamsuren et al. (2013) revealed negative correlations and the strongest signal was for the previous June and July. According to Dulamsuren et al. (2013), such difference in signal seems to be common for northern and southern conifer forests in the Altay Mountains. The negative influence of temperature was explained by an increase in the mean evaporative demand, which in turn has the potential to deteriorate the water status of trees in the main growing season. The most anxious of presented findings, are the indications that regeneration of Larix sibirica in the eastern Kazakh Saur Mountains is dramatically affected by the climate warming. This effect is so strong that present larch generation is likely to be the last one, and further forest use for timber harvest seems to be impossible in near future (Dulamsuren et al., 2013).

The next tree species also used for dendroclimatic studies was Betula pendula. We found three publications by Zhantlessova and Zhumadina, who investigated Birch in eastern Kazakhstan (Zhantlessova, 2015a; Zhantlessova, 2015b; Zhantlessova and Zhumadina, 2015). Authors collected a very big dataset of more than a 1000 cores. Unfortunately just a preliminary analysis was presented in the publications. In particular, authors indicated that the main limiting factor of birch growth is July-August precipitation. Additionally, a linkage between tree growth and solar activity was revealed. The results indicated that increasing of solar activity is associated with increased tree growth, whereas its decreasing does not have any noticeable effect (Zhantlessova, 2015a).

The last work which we found is by Panyushkina et al. (2017). In this study, the authors investigated climate-growth relationships of wild apple (Malus sieversii [Ldb.] M. Roem) in two mountain ranges in the Ile Alatau and the Zhetysu Alatau. Presented results indicated that March-August precipitation is the main limiting factor of growth at both sites. Additionally, the authors revealed a strong influence of August-February temperature in the Ile Alatau. The spectral peaks implied an influence of the East Asian Winter Monsoon (EAWM), Arctic Oscillation (AO) and Siberian High index (SH) atmospheric circulations.

One of the most interesting findings was the shifting of climatic response of apple growth in the late 1970 from one variable (winter temperatures) to another (spring precipitation) and the associated changes of spectral properties of growth variability from decadal to quasi-biennial. According to the authors this effect is connected with unprecedentedly intensified AO in winter-spring time.

3 Generalization

3.1 Pivot table

All available publications were summarized in a table and combined according to tree species in chronological order. For each study, the following parameters were specified: sampling site, tree-ring proxy type, climatic signal, climate-growth correlation and climatic reconstruction in accordance with the subject of research (Table II-1). In total the table includes 18 publications on Scots pine, 17 on Schrenk spruce, 3 on Silver birch, 2 on Siberian larch, 1 on Siever's apple and 2 on juniper. Unfortunately, in most studies only basic climate-growth relationships were investigated, so just few of them include climatic reconstructions and investigations of extreme years and periodicities.

The reconstructions presented in the table include: precipitation – 4, drought – 3, temperature – 2, runoff – 1, glacier mass balance – 1, NDVI – 1. Most of the reconstructions were built on Schrenk spruce, but there is also one reconstruction on Scots pine and one on Siberian larch. A number of studies do not describe direct climate-growth correlations, but provide information on extreme years and periodicities in the TRI, thereby making general conclusions about temporal variation of hydrothermal conditions. Unfortunately, in several publications, when the authors describe extreme years, they do not provide information on the value of the standard deviation which was exceeded, and in these cases positive and negative years were respectively indicated as (+) and (-). Also a number of rows in the table include not one but two references; this is because some publications provide results of the same study (Table II-1).

Table II-1: Dendroclimatic studies in Kazakhstan.

Reference	*Sampling sites*	*Tree-ring proxy type*	*Climatic signal*	*Climate-growth correlation (r)*	*Reconstruction (years)*
Pinus sylvestris L.					
Komin, 1969	(Kostanay region)	TRW	n/a	n/a	n/a
Grigorieva et al., 1979	Zolotoy bor (Akmola region)	TRW	(May – July) hydrothermal coefficient (Selyaninov 1958)	0.71 ± 0.06	140 (AD 1825-1964) hydrothermal coefficient

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Table II-1 (continued)

Olenin and Gurskyi, 1985	Shalday (Pavlodar region)	TRW	n/a	n/a	n/a
Olenin and Mazepa, 1988	Shalday (Pavlodar region)	TRW	n/a	n/a	n/a
Grigoriev and Karnauhova, 2013	Burabay (Akmola region)	TRW	n/a	n/a	n/a
Grigoriev and Karnauhova, 2014	Burabay (Akmola region)	TRW	n/a	n/a	n/a
Karnauhova et al., 2014a; Karnauhova et al.,2014b	Karkaraly (Karagandy region)	n/a	n/a	n/a	n/a
Karnauhova et al., 2016	Burabay (Akmola region)	EW	(May – June) temperature	-0.2 (p<n/a)	n/a
		LW	(July) temperature	-0.31 (p<n/a)	
		TRW	(May – July) temperature	0.1 (p<n/a)	
Mapitov and Zhumadina, 2015; Mapitov and Zhumadina, 2016	Shalday (Pavlodar region)	EW	(May – June) temperature	from -0.43 to -0.56 (p<n/a)	n/a
			(May – June) precipitation	from 0.42 to 0.63 (p<n/a)	
		LW	(vegetation season) precipitation	n/a	
Mapitov and Zhumadina, 2017	Beskaragay (East Kazakhstan region)	EW	(June – August) precipitation	from 0.2 to 0.5 (p<n/a)	n/a
			previous (September) precipitation	from 0.3 to 0.5 (p<n/a)	
			(May – July) temperature	from -0.2 to -0.4 (p<n/a)	
			(April) temperature	from 0.2 to 0.5 (p<n/a)	
Zhumadina and Mapitov, 2017	Beskaragay (East Kazakhstan region) and Bayanaul National Park (Pavlodar region)	EW	(May – July) precipitation	from 0.32 to 0.48 (p<n/a)	n/a
			(May – June) temperature	from -0.24 to -0.47 (p<n/a)	
		LW	(July) precipitation	from 0.5 to 0.7 (p<n/a)	
Kopabayeva et al., 2017a; Kopabayeva et al., 2017b	Burabay (Akmola region)	TRW	(May – July) temperature	from ≈ -0.31 to -0.43 (p<0.05)	n/a
			previous (November) temperature	≈ 0.35 (p<0.05)	
			previous (November – December) and current (April – June) precipitation	from ≈ 0.22 to 0.4 (p<0.05)	
Karnauhova et al., 2017	Burabay (Akmola region)	EW, LW, TRW	n/a	n/a	n/a

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Table II-1 (continued)

Karnauhova et al., 2018	Burabay (Akmola region)	EW, LW, TRW	previous November - current March and current April – July precipitation	n/a	n/a
Picea schrenkiana Fisch. et Mey.					
Grigorieva and Suslov, 1972	Ile Alatau (Almaty region)	TRW	n/a	n/a	n/a
Borscheva, 1981a	Ile Alatau (Almaty region)	TRW	(July – September) temperature and precipitation	n/a	n/a
		LW	(April – October) precipitation		
		EW	(autumn – winter) temperature and precipitation		
Borscheva, 1981c	Kungey Alatau (Almaty region)	TRW	n/a	n/a	n/a
Borscheva, 1983; Borscheva, 1986	Terskey Alatau (Almaty region)	EW	previous (October) – current (May) precipitation	with 5 years averaging, 0.8 ± 0.2 ($p<$n/a)	318 years (n/a) precipitation
			previous (September – October) – current (January – May) precipitation	with 5 years averaging, from 0.49 ± 0.18 to 0.8 ± 0.2 ($p<$n/a)	n/a
		LW	(August – September and September - October) temperature	from 0.42 ± 0.18 to 0.48 ± 0.18 ($p<$n/a)	n/a
			(June, July – August, September) precipitation	from 0.38 ± 0.18 to 0.7 ± 0.22 ($p<$n/a)	
		TRW	previous (September – October) – current (January – May) precipitation	with 5 years averaging, from 0.49 ± 0.18 to 0.8 ± 0.2 ($p<$n/a)	n/a
	Kungey Alatau (Almaty region)	LW	(July) temperature	with 5 years averaging, 0.76 ± 0.18 ($p<$n/a)	217 years (n/a) temperature
			(August – September and September – October) temperature	from 0.42 ± 0.18 to 0.48 ± 0.18 ($p<$n/a)	n/a
			(June, July – August, September) precipitation	from 0.38 ± 0.18 to 0.7 ± 0.22 ($p<$n/a)	
		EW	previous (September – October) – current (January – May) precipitation	with 5 years averaging, from 0.49 ± 0.18 to 0.8 ± 0.2 ($p<$n/a)	n/a
		TRW			n/a
	Ile Alatau (Almaty region)	LW	(July – August) precipitation	with 5 years averaging, from 0.38 ± 0.18 to 0.70 ± 0.22 ($p<$n/a)	196 years (n/a) precipitation
			(August – September and September - October) temperature	from 0.42 ± 0.18 to 0.48 ± 0.18 ($p<$n/a)	n/a
			(June, July – August, September) precipitation	from 0.38 ± 0.18 to 0.7 ± 0.22 ($p<$n/a)	
		EW	previous (September – October) – current (January – May) precipitation	with 5 years averaging, from 0.49 ± 0.18 to 0.8 ± 0.2 ($p<$n/a)	n/a
		TRW			n/a

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Table II-1 (continued)

Passmore et al., 2004	Ile Alatau (Almaty region)	TRW	(Annual) temperature	0.44 (p<n/a)	n/a
Jurina et al., 2006	Ile Alatau (Almaty region)	EW	(April - August) mean temperature	with 7 years averaging, -0.75 (p<n/a)	n/a
			previous (October) – current (April) precipitation	0.75 (p<n/a)	
Panyushkina et al., 2010	Ile Alatau (Almaty region)	TRW	(April 6th – April 30th) mean temperature	-0.61 (p<0.0001)	n/a
PAGES 2k Consortium, 2013	Ile Alatau (Almaty region)	TRW	n/a	n/a	n/a
Chen et al., 2017	Ile Alatau (Almaty region)	TRW	previous (August) – current (January) SPEI (VICENTE-SERRANO et al. 2010)	0.647 (p<0.001)	230 (AD 1785-2014) drought
Zhang et al., 2017a	Ile Alatau (Almaty region)	TRW	previous (June) – current (May) precipitation	0.63 (p<0.0001)	246 (AD 1770-2015) precipitation
Zhang et al., 2017b	Zhetysu Alatau (Almaty region)	TRW	previous (July) – current (June) scPDSI (Wells et al., 2004)	0.65 (p<0.0001)	189 (AD 1828-2016) drought
Panyushkina et al., 2018	Ile Alatau (Almaty region)	TRW (PCA Factor 1)	previous (fall) – current (January – February) precipitation	from ≈ -0.4 to -0.6 (α=0.01)	235 (AD 1779-2015) runoff
		TRW (PCA Factor 3)	(May – September) precipitation and temperature	≈ 0.3 (α=0.05)	
		TRW (PCA Factor 4)	(July – September) precipitation	from ≈ 0.35 to 0.4 (α=0.05-0.01)	
Zubairov et al., 2018a	Terskey Alatau (Almaty region)	TRW	previous (August) precipitation	0.58 (p<0.05)	183 (AD 1833-2016) precipitation
Zubairov et al., 2018b	Ile Alatau (Almaty region)	LW	(June 11th – August 4th) temperature	-0.67 (p<0.05)	n/a
		EW	previous (July 6th – November 3rd) precipitation	0.64 (p<0.05)	
		TRW	(June) SPEI	0.61 (p<0.05)	
Zhang et al., 2018	Zhetysu Alatau (Almaty region)	TRW	(July – October) NDVI	0.58 (p<0.01)	167 (AD 1850-2016) vegetation
Zhang et al., 2019	Ile Alatau (Almaty region)	TRW, $\delta^{13}C$	(previous and current growing seasons) precipitation/PDSI/SPEI	n/a	166 (AD 1850-2015) annual glacier mass balance
Betula pendula					
Zhantlessova, 2015a; Zhantlessova, 2015b	Katon-Karagay (East Kazakhstan region)	TRW	(July – August) precipitation	n/a	n/a

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Table II-1 (continued)

Zhantlessova and Zhumadina, 2015	Katon-Karagay (East Kazakhstan region)	TRW	n/a	n/a	n/a
Malus sieversii [Ldb.] M. Roem					
Panyushkina et al., 2017	Zhetysu Alatau (Almaty region)	TRW	(March – August) precipitation	from ≈ -0.25 to -0.43 (p<0.05)	n/a
	Ile Alatau (Almaty region)		(March – August) precipitation	from ≈ -0.32 to -0.52 (p<0.05)	
			(August – February) temperature	from ≈ -0.29 to -0.46 (p<0.05)	
Larix sibirica					
Shang et al., 2011	(East Kazakhstan region)	TRW	(June) temperature	0.65 (p<0.01)	310 (AD 1698-2007) temperature
Dulamsuren et al., 2013	Saur Mountains (East Kazakhstan region)	TRW	previous (May) temperature	n/a	n/a
			previous (June – July) and current (July) temperature		
			previous (July) and current (April and July) precipitation		
			current (February) precipitation		
Juniperus seravschanica Kom., *Juniperus semiglobosa* Reg., *Juniperus turkestanica* Kom.					
Borscheva 1978	Tian Shan Mountains (Almaty region)	TRW	n/a	n/a	n/a
Mukhamedshin and Sartbayev, 1981	Tian Shan Mountains (South Kazakhstan regions)	TRW	(July) temperature (low and mean altitude)	from -0.72 to -0.89 (p<n/a)	n/a

3.2 Climate-growth relationships

Comparing studies in accordance with tree species, we can see that in general results obtained by different authors are in agreement with each other. Studies on Schrenk spruce indicate positive influence of previous autumn – current spring precipitation and negative influence of high summer temperatures on tree growth. These are the main limiting factors of growth, according to results presented in the majority of publications (Borscheva, 1983; Jurina et al., 2006; Zhang et al., 2017a). Precipitation from the previous autumn to current spring provides necessary moistening of the soil in the beginning of the growing season which is beneficial and highly important for tree growth (Borscheva, 1983; Chen et al., 2017; Zhang et al., 2017a). In turn, high summer temperatures in conjunction with low precipitation can affect the production of sugars and be considered as a manifestation of drought stress (LaMarche, 1974). Variation of dry/wet conditions, extreme years and periodicities detected in the tree-ring series are also in good agreement, which confirms reliability of detected climatic signals. For example, several studies revealed common extreme dry years (±2σ) occurred in 1879, 1917 and 1945, and common periodicities were associated with the ENSO, TBO and NAO (Chen et al., 2017; Zhang et al., 2017a; Zhang et al., 2017b; Zubairov et al., 2018a; Panyushkina et al., 2018) (Figure II–2). Also, variation of the Ili River flow reconstructed by Panyushkina et al. (2018) is consistent with variation of dry/wet conditions revealed in reconstructions presented by Chen et al. (2017) and Zhang et al. (2017a). The exact values and dates of extreme years, periodicities and temporal variation of different environmental conditions are available in the supplementary materials (Table SM II–1).

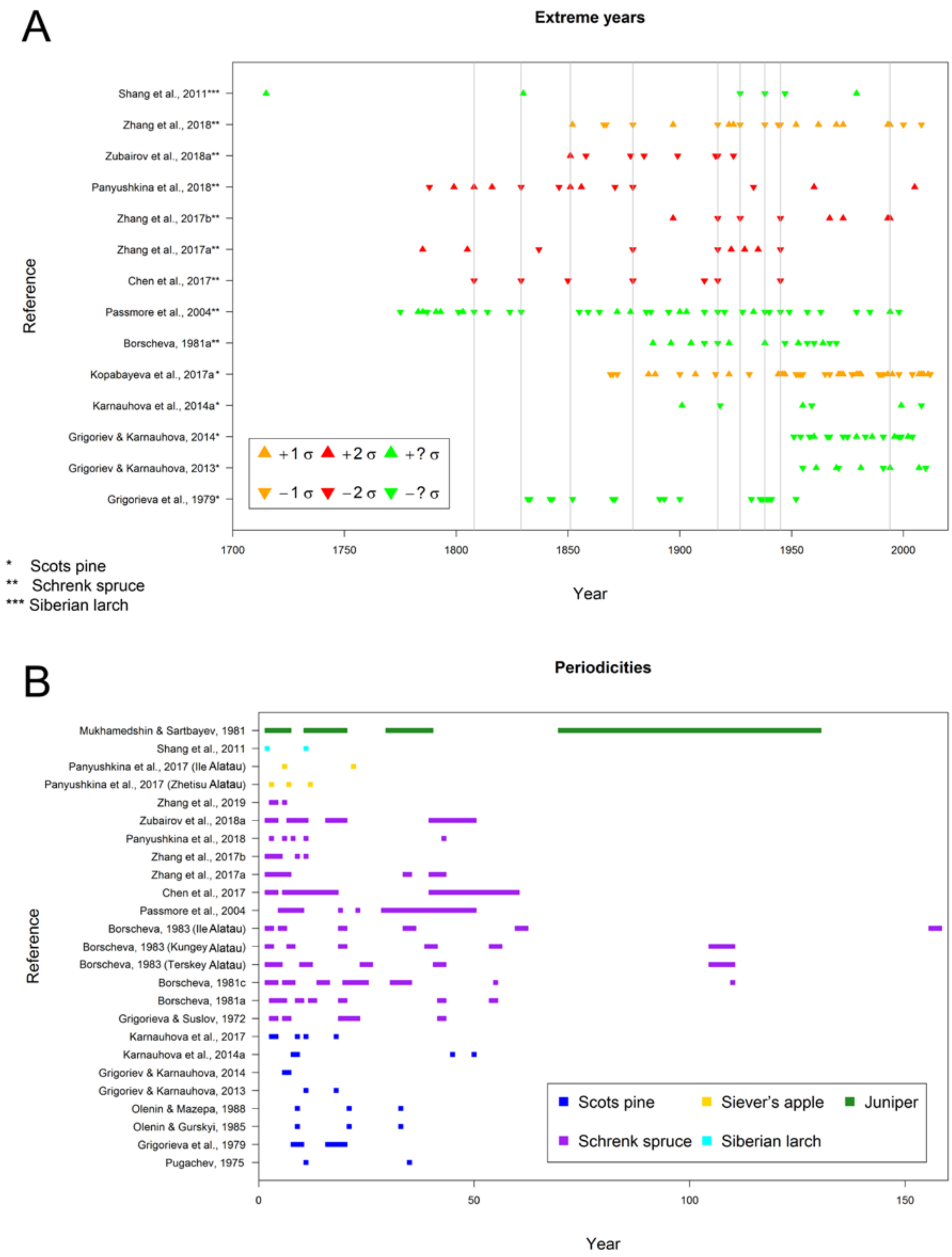

Figure II-2: (A) Revealed extreme years. Grey lines indicate common extreme years. Color and position of triangles indicate the sign and degree of deviation of values in the corresponding year. (B) Revealed periodicities. When a single study provided information on several mountain ranges, then a particular mountain range is specified in parentheses.

Of course there are still some divergences, or additional climatic signals revealed in tree-ring series. For example, some authors reported on positive influence of warm winters (Chen et al., 2017) or on negative influence of April temperatures on Schrenk spruce growth (Panyushkina et al., 2010). This can be associated with several factors, such as age of trees or growing conditions. For example, the time period of LW formation for old and young trees is different. Formation of LW, which is mainly driven by the temperature conditions for young trees, has a longer formation period (June – August), whereas for old trees the period is shorter (end of June – second half of July). While EW growth in general is influenced by the cold-period weather, LW is primarily affected by the hydro-thermal conditions during summer-autumn of the current year (Borscheva, 1983; Zubairov et al., 2018b). These differences are also enhanced by the influence of hydro-thermal conditions which vary with altitude. Length of dry season and lower temperatures at the upper tree-limit are responsible for stretching of the ontogenesis of Schrenk spruce over time and for the offset of growing season (Borscheva, 1983). Additionally, precipitation increasing with altitude leads to decreased dependency of Schrenk spruce growth from humidification conditions, while influence of temperature conditions increases (Borscheva, 1981d; Jurina et al., 2006). This effect is reflected in the correlations analysis results, when tree growth shows strongest correlations with precipitation at the low altitudes (Zhang et al., 2017a) and with temperature near the upper tree-limit (Panyushkina et al., 2010).

Variation of climate with latitude and indirect influence of other factors like orography also strongly affects MS of Schrenk spruce. Reduction of precipitation from West to East in northern Tian Shan sometimes leads to a higher sensitivity to precipitation rather than to temperature, even at the upper tree-limit (Zubairov et al., 2018a). Conversely, in deep and narrow gorges of Kungey Alatau, radial growth of Schrenk spruce is more dependent on temperature rather than humidification (Borscheva, 1983; Borscheva, 1986). Thus, direct growth-controlling factors like precipitation or temperature can be strongly affected by indirect factors like orography, soil characteristics, presence or absence of permafrost, etc. Complexity of these interconnections between growth-controlling factors has very often leaded to contrasting conclusions. According to Borscheva (1983), MS of Schrenk spruce grows with age, whereas in results presented by Wu et al. (2013) and Zubairov et al. (2018b) younger trees appeared to be more sensitive. Another example is the variation of MS, when it grows with altitude in the Ile Alatau (Kolov et al., 2003) but decreases in the central Tian Shan (Wang et al., 2005). In first case increase in MS can be explained to some extent with the presence of permafrost. Borscheva indicated, that the closer the permafrost to the earth surface, the higher the LW content and the higher the MS, which can vary from 0.33 to 0.44 (Borscheva, 1983). In turn, decreasing of MS with altitude in the central Tian Shan probably can be associated with decreasing amounts of precipitation from West to East (Aizen et al., 1997; Bolch, 2007), which is of course more pronounced at lower tree limit. And since we know that Schrenk spruce growth is more dependent on humidification conditions (Borscheva, 1983; Chen et al., 2017; Zhang et al., 2017a) such changes in precipitation should result in increasing of MS towards lower tree limits. This assumption can explain decrease of MS revealed in the Terskey Alatau, (from 0.36 at 2230 m a.s.l. to 0.24 and 0.16 at 2500 and 2650 m a.s.l. respectively) and in the Zhetysu Alatau, (from 0.38 at 1450 m a.s.l. to 0.18 – 0.21 at 2000-2050 m a.s.l.) (Zhang et al., 2017b; Zhang et al., 2018; Zubairov et al., 2018a).

Considering and comparing studies on Scots pine, we see that the number and quality of studies is lower than on Schrenk spruce; however several common features of climate-growth relations can already be noted. For example, most researchers indicate positive correlations with summer precipitation and negative influence of May – July temperatures (Karnauhova et al., 2016; Mapitov and Zhumadina, 2017; Kopabayeva et al., 2017a). This appeared to be due to high evapotranspiration and moisture deficit in the soil in northern Kazakhstan, which affect xylem growth (Mapitov and Zhumadina, 2016; Kopabayeva et al., 2017a). Some researchers also note positive influence of previous autumn-winter precipitation, explaining this by the fact that deep snow cover provides additional moisture in dry season and frost protection during winter months (Mapitov and Zhumadina, 2017; Kopabayeva et al., 2017a). Apart from similarities, certain differences in climate-growth relationships can also be noted. For example, correlation analysis indicated that Scots pine growth in the Beskaragay and in the Burabay forests is dependent on previous year temperature and precipitation (Mapitov and Zhumadina, 2017; Kopabayeva et al., 2017a), whereas in the Shalday forests such dependency cannot be found (Mapitov and Zhumadina, 2015; Mapitov and Zhumadina, 2016). Such differences can be associated with differences in climate due to different elevations of these sites, and other local features, like proximity of big water bodies. The Burabay forests are located at elevations around 360-850 m a.s.l., whereas the Shalday forests are located at elevations around 150 m a.s.l. and the amount of precipitation in this region in general varies from 250 mm in the lowland to 400 mm in the hilly part, with a corresponding decrease of temperatures. The increasing of precipitation with altitude is also reflected in a slight decreasing of MS, from

0.27 at 360-440 m a.s.l. to 0.23 at 750-850 m a.s.l. which again confirms high dependency of Scots pine growth on the moisture level (Kopabayeva et al., 2017a).

A certain consistency between results of different studies can also be seen by comparing available climatic reconstructions. Unfortunately the climatic reconstructions we found are relatively short. There is only one reconstruction which exceeds 300 years (Figure II–3). The majority of old reconstructions, for example original reconstructions by Borscheva have not been found yet.

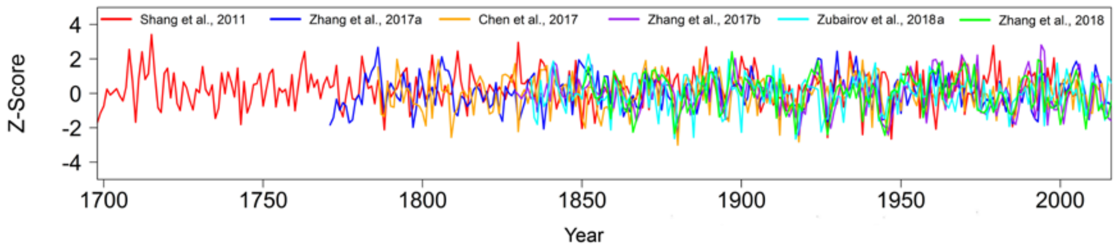

Figure II-3: A comparative graph of climatic reconstructions.

For example, it is interesting to note, that reduction in diameter growth of Larix sibirica in eastern Kazakhstan since 1970s which was mainly connected with increased temperatures Dulamsuren et al. (2013), coincides with the beginning of the periods of sparse vegetation in the Zhetysu Alatau (Zhang et al., 2018), the decreasing trend of the Tsentralniy Tuyuksuyskiy glacier mass balance (Zhang et al., 2019), the low flow of the Ile River (Panyushkina et al., 2018) and with dry conditions in the entire southeastern Kazakhstan (Chen et al., 2017; Zhang et al., 2017a; Zubairov et al., 2018a). It was also in 1970s, that a shift of climatic response of apple growth (Panyushkina et al., 2018) and a decrease of the temperature signal of Schrenk spruce was detected (Zubairov et al., 2018b).These results are also in agreement with results of other, more extensive studies conducted by D'Arrigo et al. (2008), which revealed a reduction of sensitivity and changes in the structure of temperature signal in radial tree growth since the middle of the 20th century in northern forests and with recent results published by Babst et al. (2019), revealing a significant decrease of temperature response in temperate and boreal tree growth.

In contrast, in northern Kazakhstan, climatic conditions became more favorable. Increase of precipitation, from previous October to current July and increased summer temperatures, resulted in increased tree-ring widths of the Scots pine, starting from 1940s (Kopabayeva et al., 2017a). A similar trend was found in other parts of northern hemisphere (D'Arrigo et al., 2000; George and Ault, 2014; Cook et al., 2015). Based on these observations, the authors anticipate respective increase in radial growth of trees in other ecosystems and areas, where temperature is the main limiting factor of growth, for example in deep and narrow gorges or near the upper tree limits, and on permafrost territories. Such effect was already noted in previous studies by Borsheva et al. (1983) in spruce forests of the Issyk, Orta-Turgen and Chin-Turgen river basins. According to their results permafrost reduces the time period of cambium activity, thereby reducing the radial growth of trees. Increased temperatures and accelerated thawing of soils should reduce this negative influence (Borsheva et al., 1983).

4 Studies on other subfields of dendrochronology

First, we would like to mention several studies investigating possible way of dating natural hazards. The first study published by Severskiy et al. (1977) presented results of investigation of avalanche frequency assessment in the Ile Alatau using Schrenk spruce. The authors revealed, that periods between increasing of avalanche activity is equal to 3-10 years. Obtained results indicated, that the high avalanche activity most likely occurred in: 1866-1872, 1885-1888, 1890-1892, 1895-1897, 1901-1902, 1905-1907, 1912-1915, 1926-1927, 1936-1937, 1941-1942, 1945-1948, 1951-1952, 1955-1957, 1959-1961, 1966, 1967 and 1969 (Severskiy et al., 1977). In the next study published by Yadav and Kulieshius (1992) authors investigated influence of earthquakes on the Schrenk spruce growth, in the Ile Alatau Mountains. This study revealed a strong growth suppression, which lasted up to 15 years after the 1887 earthquake. This suppression was attributed to the tilting of trees. The negative influence on tree growth caused by the earthquakes, was also described in the study by Passmore et al. (2004), which was conducted in the same region, and revealed evidence of the 1887 and 1911 earthquakes in the tree rings. In 2001 was published a book by Gorbunov, A.P. and Seversky, E.V., where authors reviewed the history and conditions of debris flows occurrence in the Ile Alatau. The application of dendrochronological methods helped them to reveal at least 6 large-scale debris flows in the Issyk river valley during the last 1100-1500 years (Gorbunov and Seversky, 2001). In more recent studies published by Passmore et al., authors investigated the spatial patterns, the chronology of landforms and sediment assemblages in the Bolshaya Almatinka river valley. The results revealed at least 6 new major debris-flow assemblages, occurred in the following periods: ca. 1607-1633, ca. 1702-1728, ca. 1725-1751, ca. 1769-1795 (Passmore et al., 2004; Passmore et al., 2008). According to Passmore et al., (2008), the main trigger of large-scale debris-flows in the region are glacial lake outbursts, which is turn associated with the intense glacier ablation. Therefore, it would be interesting to compare the information presented with the glacier mass balance reconstruction like the one published by Zhang et al., (2019). Unfortunately, this reconstruction is relatively short and goes back only until the 1850s. Hopefully, in the future it will be extended and provide additional information for a deeper understanding of interconnections between climate, glaciers mass balance and geomorphological processes in the region. In 2014 a work by Langenwalter K. (2014) was published. The study was also conducted in the Bolshaya Almatinka river valley. But at this time the author investigated an applicability of dendrochronological methods for dating of landslides. Unfortunately, the results didn't provide a clear conclusion, which according to the author was due to methodological limitations (e.g. the author couldn't collect cross sections and apply a methodology suggested by Strunk, H. (1997). The next interesting paper was published by Mazarzhanova et al. (2017), where the authors analyzed tree rings structure of Pinus sylvestris for dating of the forest fires in the Burabai region. Determining fire scars, they revealed at least 15 fires during the last 300 years. Four of them occurred in 1759, 1779, 1871 and 1952 had long-term negative effect on tree growth sometimes lasting up to 10 years, and seven occurred in 1759, 1797, 1824, 1833, 1852, 1871 and 1899 can be considered as large-scale fires covering wide areas, because fire scars in these years were detected at sampling sites, located about 8 km away from each other (Mazarzhanova et al., 2017). Another interesting issue is the influence of pest and other diseases on tree growth. Here we need to mention the study published by Mukhamadiev et al. (2014). In this work, the authors investigated the history of bark beetle outbreaks in particular Ips hauseri in the Ile Alatau Mountains. Special interest in this issue has arisen after two severe cyclonic storms in 2011, which damaged several hundred hectares of spruce forests and subsequent intensive growth of bark beetle populations. The results showed, that, at least during last 200 years, there was no evidence of severe bark beetle outbreaks in the region (Mukhamadiev et al., 2014). The last work, which we would like to mention is a small study published by Mironova A.S. (2013), where she presented results of dendrochemical analysis, using samples collected in the Beskaragay region, located not far from the Semipalatinsk Test Site, which was the primary testing venue for the Soviet Union's nuclear weapons. Results showed high radionuclide content in pine ash especially for Zn and Sr in period from 1942 to 1966 (Mironova, 2013). Finally, many authors note a strong negative influence of the anthropogenic factors, which include: overgrazing, overharvesting through illegal cutting and degradation from excessive recreation use (Borscheva, 1983; Kushlin et al., 2003; Dulamsuren et al., 2013; Karnauhova and Grigoriev, 2016). All studies mentioned in this paper provide results that can be very useful, when we want to differentiate effects of climatic extremes from other forest stand disturbances.

5 Conclusion

As we see, despite dendroclimatology in Kazakhstan being in its infancy, there is already a good foundation for further investigations, laid back in the days of the Soviet Union. We have reviewed 43 studies, all of which have been published within last 40 years.

Our review demonstrated large range in the quality, number and variety of performed dendroclimatic studies for different tree species and from different parts of Kazakhstan. At the current stage, the most thorough studies have been performed in southern Kazakhstan on Schrenk spruce. Comparative analysis of results presented in these studies allowed us to highlight common patterns of climate growth relationships and variations of hydroclimatic parameters in the region. At the same time, studies on other tree species are significantly inferior, either qualitatively or quantitatively. Such difference needs to be addressed and can be achieved through closer cooperation between different research groups. Such cooperation could significantly improve tree-ring network of Kazakhstan and help bringing dendroclimatological studies up to international standards. A number of authors also pointed to the necessity of further investigations, specifically more spatially extensive and longer tree-ring chronologies, in order to clarify certain climatic features and how they affect tree growth (Chen et al., 2017; Zhang et al., 2017b; Zubairov et al., 2018a). Indeed, even compared to neighboring countries such as Russia, China and Kyrgyzstan, chronologies built in Kazakhstan are much shorter. Suffice to say that no chronology exceeding 500 years has been published yet. Probable solution for this issue could be a usage of fossil wood and archeological wood. Another big option which could contribute to development of dendroclimatology in Kazakhstan would be an application of new methods like stable isotope and wood anatomy.

We hope that this review will be useful for researchers who are conducting or planning to conduct dendroclimatic studies in Kazakhstan. Unfortunately, there is a possibility that we have missed some publications in this review, but nevertheless we believe that even in its current form; it gives a general concept and reflects the stages of dendroclimatology development in Kazakhstan.

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Supplementary Material

Table SM II-1: Supplementary data for table 1.

Reference	*Sampling sites*	*Tree-ring proxy type*	*Periodicities (years)*	*Extreme years*	*Variation of conditions (years)*
Pinus sylvestris L.					
Komin, 1969	(Kostanay region)	TRW	n/a	n/a	n/a
Pugachev, 1975; Pugachev, 1986	Arakaragay, Amankaragay, Nauruzum, Tersek (Kostanay region)	TRW	11, 35	n/a	(growth decrease) 1982-1990, 1995-2000, 2005-2009, 2014-2018
Grigorieva et al., 1979	Zolotoy bor (Akmola region)	TRW	~ 8-10, 16-20	(-) 1832-1833, 1842-1843, 1852, 1870-1871, 1891, 1893, 1900, 1932, 1936-1941, 1952	n/a
Olenin and Gurskyi, 1985	Shalday (Pavlodar region)	TRW	10.3, 21, 33	n/a	n/a
Olenin and Mazepa, 1988	Shalday (Pavlodar region)	TRW	10.3, 21, 33	n/a	n/a
Grigoriev and Karnauhova, 2013	Burabay (Akmola region)	TRW	11.5, 18.3	(+) 1961, 1970, 1981, 1994, 2007 (-) 1955, 1971, 1991, 2010	n/a
Grigoriev and Karnauhova, 2014	Burabay (Akmola region)	TRW	6.7, 6.9	(+) 1960, 1979, 1986, 1996, 2002 (-) 1951, 1954, 1958, 1966-1967, 1973-1975, 1983, 1991, 1998-1999, 2004	n/a
Karnauhova et al., 2014a; Karnauhova et al.,2014b	Karkaraly (Karagandy region)	n/a	8.8, 9.5, 45, 50	(+) 1918, 1959, 2008 (-) 1901, 1955, 1999	n/a
Karnauhova et al., 2016	Burabay (Akmola region)	EW LW TRW	n/a	n/a	n/a
Mapitov and Zhumadina, 2015; Mapitov and Zhumadina, 2016	Shalday (Pavlodar region)	EW LW	n/a	n/a	n/a
Mapitov and Zhumadina, 2017	Beskaragay (East Kazakhstan region)	EW	n/a	n/a	n/a

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Table SM II-1 (continued)

Zhumadina and Mapitov, 2017	Beskaragay (East Kazakhstan region) and Bayanaul National Park (Pavlodar region)	EW	n/a	n/a	n/a
		LW			
Kopabayeva et al., 2017a; Kopabayeva et al., 2017b	Burabay (Akmola region)	TRW	n/a	(+ 1σ) 1886, 1889, 1907, 1922, 1944-1947, 1971-1973, 1979-1981, 1993, 1995, 2007-2009, 2011 (- 1σ) 1869-1870, 1872, 1900, 1916, 1931, 1952-1955, 1965, 1967, 1977, 1989-1991, 1998, 2004, 2012	n/a
Karnauhova et al., 2017	Burabay (Akmola region)	EW, LW, TRW	~ 3-4, 9, 11, 18	n/a	n/a
Karnauhova et al., 2018	Burabay (Akmola region)	EW, LW, TRW	n/a	n/a	n/a
Picea schrenkiana Fisch. et Mey.					
Grigorieva and Suslov, 1972	Ile Alatau (Almaty region)	TRW	~ 3-4, 6-7, 19-23, 42-43	n/a	n/a
Borscheva, 1981a	Ile Alatau (Almaty region)	TRW	~ 3-4, 5-6, 9-10, 12-13, 19-20, 42-43, 54-55	(+) 1888, 1896, 1905, 1922, 1938, 1953, 1964 (-) 1911, 1917, 1947, 1957, 1960, 1967, 1970	n/a
		LW		n/a	
		EW			
Borscheva, 1981c	Kungey Alatau (Almaty region)	TRW	2, 3-4, 6-8, 15-17, 20-25, 31-35, 55, 110	n/a	
Borscheva, 1983; Borscheva, 1986	Terskey Alatau (Almaty region)	EW	~ 7-8, 14-16, 27-29, 47-49, 110-115	n/a	(wet autumn-spring) first half of XVIII, second half of XIX (dry autumn-spring) second half – end of XVII, end of XVIII – beginning of XIX (wet summer) end of XVII – middle of XIX (dry summer) second half of XVII, beginning of XX centuries
		LW	~ 9-10, 25-27, 38-40, 76-78, 220-230		
		TRW	~ 2-3, 4-5, 10-12, 24-26, 41-43, 105-110		

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Table SM II-1 (continued)

Borscheva, 1983; Borscheva, 1986	Kungey Alatau (Almaty region)	LW	~ 2-3, 6-7, 16-18, 31-33, 62-64, 200-210	n/a	(wet autumn-spring) first half of XVIII, second half of XIX (dry autumn-spring) second half – end of XVII, end of XVIII – beginning of XIX (wet summer) first end of XVII – beginning of XVIII (dry summer) middle of XVII and XIX centuries
		EW	~ 2-3, 7-8, 18-20, 23-25, 42-44, 110-115		
		TRW	~ 2-3, 7-8, 19-20, 39-41, 54-56, 105-110		
	Ile Alatau (Almaty region)	LW	~ 2-3, 5-6, 20-22, 40-42, 76-78, 240-250	n/a	(wet autumn-winter) first half of XVI, end of XVII, beginning of XIX, middle of XX (dry autumn-winter) middle of XV, beginning of XVII, middle of XVIII and XIX (wet summer) middle of XV – middle of XVI, middle of XVII – end of XVIII and XX centuries
		EW	~ 4-5, 12-14, 29-31, 63-65, 132-134		
		TRW	~ 2-3, 5-6, 19-20, 34-36, 60-62, 156-158		
Passmore et al., 2004	Ile Alatau (Almaty region)	TRW	~ 19, 23, 30-50	(+) 1783, 1785, 1791, 1793, 1803, 1872, 1878, 1900, 1903, 1933, 1994 (-) 1775, 1787, 1801, 1808, 1814, 1824, 1829, 1855, 1859, 1864, 1885, 1887, 1895, 1911, 1917, 1920, 1928, 1938, 1940, 1945, 1949, 1957, 1963, 1979, 1985, 1998	n/a
Jurina et al., 2006	Ile Alatau (Almaty region)	EW	n/a	n/a	n/a
Panyushkina et al., 2010	Ile Alatau (Almaty region)	TRW	n/a	n/a	n/a
PAGES 2k Consortium, 2013	Ile Alatau (Almaty region)	TRW	n/a	n/a	n/a
Chen et al., 2017	Ile Alatau (Almaty region)	TRW	~ 2-4, 6-11, 10-15, 11-18, 40-60	(- 2σ) 1808, 1829, 1850, 1879, 1911, 1917, 1945	(wet) 1823-1845, 1866-1877, 1882-1903, 1922-1941, 1964-1973, 1986-2004 (dry) 1806-1822, 1846-1865, 1904-1921, 1974-1985
Zhang et al., 2017a	Ile Alatau (Almaty region)	TRW	~ 2-7, 34-35, 40-43	(+ 2σ) 1785, 1805, 1923, 1929, 1935 (- 2σ) 1837, 1879, 1917, 1945	(wet) 1779-1811, 1838-1859, 1885-1906, 1921-1940, 1953-1972, 1997-2012 (dry) 1770-1778, 1812-1837, 1860-1884, 1907-1920, 1941-1952, 1973-1996, 2012-2015

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Table SM II-1 (continued)

Panyushkina et al., 2018	Ile Alatau (Almaty region)	TRW (PCA Factor 1) TRW (PCA Factor 3) TRW (PCA Factor 4)	2.9, 5.7, 8.0, 11.6, 42.7	(+ 2σ) 1799, 1808, 1816, 1851, 1856, 1960, 2005 (- 2σ) 1788, 1829, 1846, 1871, 1879, 1933	(high flow) 1793-1809, 1850-1857, 1886-1909, 1952-1962, 2001-2013 (low flow) 1825-1850, 1865-1885, 1916-1938, 1975-2000
Zubairov et al., 2018a	Terskey Alatau (Almaty region)	TRW	~ 2-4, 7-11, 16-20, 40-50	(+ 2σ) 1851 (- 2σ) 1858, 1878, 1884, 1899, 1916, 1917, 1924	(wet) 1847-1858, 1889-1916, 1934-1966, 1992-2008 (dry) 1858-1889, 1916-1934, 1966-1992, 2008-2015
Zubairov et al., 2018b	Ile Alatau (Almaty region)	LW EW TRW	n/a	n/a	n/a
Zhang et al., 2018	Zhetysu Alatau (Almaty region)	TRW	n/a	(+ 1σ) 1852, 1897, 1922, 1924, 1952, 1962, 1970, 1973, 1993, 1994 (- 1σ) 1866, 1867, 1879, 1917, 1927, 1938, 1944, 1945, 2000, 2008	(dense vegetation) 1860-1870, 1891-1907, 1950-1974 (sparse vegetation) 1871-1890, 1908-1949, 1975-2006
Zhang et al., 2019	Ile Alatau (Almaty region)	TRW, $\delta^{13}C$	2.6, 2.7, 3.3, 4.4, 5.6, 6.2	n/a	(increasing trend) 1863-1902, 1917-1935, 1944-1967 (decreasing trend) 1850-1862, 1903-1916, 1936-1943, 1968-2015
Betula pendula					
Zhantlessova, 2015a; Zhantlessova, 2015b	Katon-Karagay (East Kazakhstan region)	TRW	n/a	n/a	n/a
Zhantlessova and Zhumadina, 2015	Katon-Karagay (East Kazakhstan region)	TRW	n/a	n/a	n/a
Malus sieversii [Ldb.] M. Roem					
Panyushkina et al., 2017	Zhetysu Alatau (Almaty region)	TRW	3.3, 7.1, 11.6	n/a	n/a
	Ile Alatau (Almaty region)		6.3, 21.8		

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Table SM II-1 (continued)

Larix sibirica					
Shang et al., 2011	(East Kazakhstan region)	TRW	2, 11	(+) 1715, 1830, 1979 (-) 1927, 1938, 1947	(warm) 1707-1720, 1757-1770, 1805-1839, 1872-1906 (cold) 1721-1756, 1840-1871, 1906-1924
Dulamsuren et al., 2013	Saur Mountains (East Kazakhstan region)	TRW	n/a	n/a	n/a
Juniperus seravschanica Kom., *Juniperus semiglobosa* Reg., *Juniperus turkestanica* Kom.					
Borscheva 1978	Tian Shan Mountains (Almaty region)	TRW	n/a	n/a	n/a
Mukhamedshin and Sartbayev, 1981	Tian Shan Mountains (South Kazakhstan regions)	TRW	~ 2-7, 11-20, 30-40, 70-130	n/a	(relatively cold and wet vegetation periods) VIII, IX, end of XIII – middle of XV, beginning of XIX, middle of XVIII, XIX and XX (relatively warm vegetation periods) middle of XI – end of XIII, middle of XVIII centuries

Chapter III:
Searching for the best correlation between climate and tree rings in the Trans-Ili Alatau, Kazakhstan

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Abstract

The result of correlation analysis between tree-ring growth and climate is the key indicator in dendroclimatic investigations. Combinations of different climate datasets with different tree-ring parameters of Schrenk spruce (Picea schrenkiana Fisch. et Mey.), give different correlation results. Samples for this study were collected in spruce forests of northern Tian Shan in the southeastern part of Kazakhstan. Several combinations of monthly, daily, gridded and station climate data with earlywood (EW), latewood (LW), total ring width (TRW) of young, old and mixed (old and young) trees were checked for the period from 1926 to 1982. EW showed the best correlations with precipitation, LW with temperature and TRW with Standardized Precipitation-Evapotranspiration Index (SPEI). Correlation analysis indicates that daily climate data in combination with EW and LW provide best results. Strongest correlation with precipitation was found for EW of old trees, for the period July 6th – November 3rd (previous year), r = 0.64 (p<0.05). LW of age-mixed trees showed correlation with temperature of current year. Strongest correlations: with average temperature, for the period June 11th – August 4th, r = -0.67; with maximum temperature, for the period June 25th – July 17th, r = -0.66 (p<0.05) and with minimum temperature for the period June 11th – august 4th, r = -0.64 (p<0.05). TRW of young trees showed the strongest correlation with the Standardized Precipitation-Evapotranspiration Index 12, for June of current year, r = 0.61 (p<0.05). Finally a shifting of strongest correlation between EW of mixed trees and precipitation was found. The strongest correlations with gridded data were found in previous July and with station data in previous October. This study provides new information for understanding the relationships between tree-ring growth and climate.

1 Introduction

The main goal of dendroclimatic investigations is the reconstruction of different climatic parameters. In order to do this reconstruction, we need to understand which climatic signal we have in our tree rings. For this purpose we use correlation analysis, but the results of this analysis always depends on many parameters: sampling site, preparation of the samples, standardization process and climate dataset which are used, all these influence the final results (Schweingruber, 1996). In order to start a new research at a new place, we always have to check what kind of information is stored in our samples. The dendroclimatic investigations in Kazakhstan started in Soviet times and were especially intensive in the southeastern part of Kazakhstan in Tian Shan Mountains, where forests are dominated by Schrenk spruce (Picea schrenkiana Fisch. et Mey.). The first thorough dendroclimatic research in Kazakhstan using Schrenk spruce was conducted by Borscheva NM from the 1970s to the 1990s. She found that sensitivity of Schrenk spruce grows from West to East, from the Trans-Ili Alatau Range to the Kungey and the Terskey Alatau Ranges, which is connected with a decrease of precipitation in this direction (Borscheva, 1983). In the mountains, variations of temperature and precipitation regime are also highly influenced by altitudinal zonation (elevation and topography). In literature usually spruce forests in Tian Shan are divided in three belts: lower – from lower tree limit to 2100-2200 m a.s.l., middle – from 2100-2200 to 2400-2500 m a.s.l. and upper – from 2400-2500 m a.s.l. to upper tree limit, this division is based on differences in climatic conditions (Roldugin, 1970; Kolov et al., 2003). In northern Tian Shan the coefficients of sensitivity for earlywood (EW), latewood (LW) and total ring width (TRW), vary from 0.15 to 0.27 (Borscheva, 1983). According to Borscheva, in general old trees have higher LW content, and show higher sensitivity compared to young trees (Borscheva, 1983). Correlation analysis showed that increment of EW is influenced by cold-period weather at both upper and lower tree-limits. For the LW formation the dominant factors are precipitation from June-July to August-September of the current year and temperature from the second half of the summer to beginning of the autumn (Borscheva, 1983). Borscheva showed that growth is influenced by precipitation and temperature, but the dominant factor is autumn-winter precipitations of previous year and current year's spring precipitation. She found that the influence of humidification and thermal conditions of the previous vegetation year affects only the annual variability through the formation of vegetative buds and needles (Borscheva, 1981a; Borscheva, 1981b; Borscheva, 1981c; Borscheva, 1981d; Borscheva, 1983; Borscheva, 1986). Other researchers have also noted the importance of the previous year precipitation, which is explained by enhanced soil moisture availability (Gan, 1970; Chen et al., 2017; Zhang et al., 2017; Panyushkina et al., 2018). We found only 5 published dendroclimatic studies conducted in the Trans-Ili Alatau since the 1990s (Table III–1), and in general all published results are in agreement with Borscheva's. But we can obviously see the difference in input data, some researchers collected samples at upper, and others at lower tree lines. Some of them used only weather station data and others also used gridded datasets. One group investigated correlations with yearly, a second with monthly and a third with daily climate data (Passmore et al., 2004; Panyushkina et al., 2010; Zhang et al., 2017; Panyushkina et al., 2018). Borscheva investigated signals from EW and LW, whereas, other researchers used only TRW. Taking this into consideration, we set a goal to investigate how different combinations of input data affect correlation results. Also, this will be the first correlation analysis between EW, LW and daily climate data in the Trans-Ili Alatau, we hypothesize that this combination can provide the strongest correlations and more precise seasonality window of climatic signal in the tree rings variation.

Table III-1: Dendroclimatic studies in the Trans-Ili Alatau based on Schrenk spruce.

Reference	Tree-ring proxy type	Forest belt	Detrending Method	Climate data used	Meteorological station	Climatic signal	Climate-growth correlation
Borscheva (1983)	LW	Lower	n/a	Monthly station data	n/a	Jul-Aug precipitation	With 5 years averaging, from r = 0.38 ± 0.18 to 0.70 ± 0.22 (p<n/a)
Passmore et al. (2004)	TRW	Middle	n/a	Monthly station data	Bolshaya Almatinka Lake, Mynzhilki and Ust Gorelnik	Annual temperature	r = 0.44 (p<n/a)
Panyushkina et al. (2010)	TRW	Upper	Hugershoff growth curve	Monthly and daily station data	Narin	April 6th – April 30th mean temperature	r = -0.61 (p<0.0001)
Chen et al. (2017)	TRW	Lower	Cubic smoothing spline, with 50% frequency-response at 70 years	Monthly station and gridded data	Almaty	SPEI[a] (VICENTE-SERRANO et al. 2010) (previous August – current January)	r = 0.647 (p<0.001)
Zhang et al. (2017)	TRW	Lower	100 yr – spline curve	Monthly station and gridded data	Almaty	previous June – current May precipitation	r = 0.63 (p<0.0001)

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Table III-1 (continued)

Panyushkina et al. (2018)	TRW	All forest belts	Cubic smoothing spline, with 50% frequency-response at a wavelength of 2/3 the sample series length	Monthly station and gridded data	Almaty	previous fall – current January – February precipitation	r ≈ from -0.4 to -0.6 (α=0.01)
						July – September precipitation	r ≈ from 0.35 to 0.4 (α=0.01-0.05)
						May – September precipitation and temperature	r ≈ 0.3 (α=0.05) Significance estimated by Monte Carlo method (Meko et al. 2011)

[a]SPEI the Standardized Precipitation-Evapotranspiration Index.

2 Data and Methods

2.1 Sampling site and chronologies development

Schrenk spruce, (Picea schrenkiana Fisch. et Mey) samples were collected in the lower tree-line (1970 m above sea level) of the Trans-Ili Alatau Range, Kazakhstan (43.05°N, 76.45°E) near the Aksay gorge, in September 2016 (Figure III–1). Sampling was conducted on a north-facing slope (inclined at 20°-25°) with a shallow soil layer following standard dendrochronological procedures outlined in Speer (2010). At least 2 cores from a total of 21 trees were sampled from individuals without signs of injury or diseases, with 38 cores suitable for further analysis.

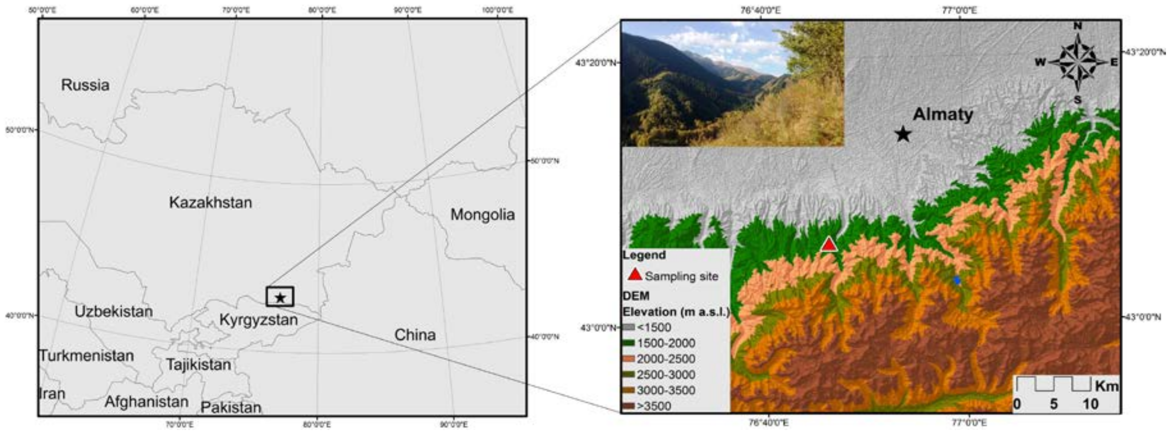


Figure III-1: Study region and photo from the site. The Digital Elevation Model (DEM) was obtained using the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 image (Tachikawa et al. 2011). The map is generated by ArcGIS 10.3 (https://www.arcgis.com/).

Cores were dried, mounted and polished with progressively finer sandpapers. Prepared samples were scanned at 1200 dpi and measured in WinDENDRO (Regent Instruments Canada Inc., 2009). The WinDENDRO is a semi-automatic system. The rings are detected based on light intensity differences and then checked visually on presence of false/missed rings or misclassifications. Measurements for EW, LW, and TRW were divided in groups based upon tree age and includes, i) old trees (12 cores from 7 trees with a mean segment length of ~150 years), ii) young trees (12 cores from 7 trees with a mean segment length of ~ 77 years), and iii) mixed old and young trees (38 cores from 21 trees with a mean segment length of ~ 103 years). All series were visually cross-dated in the TSAPWin program (Time Series Analysis and Presentation for Dendrochronology and Related Applications; version 4.67c © 2002-2011 Rinntech), checked using the COFECHA program (Version 6.06P © 1997-2004 Absoft Corporation) and corrected if it was necessary (Holmes, 1983). Then the ARSTAN program (AutoRegressive STANdardization; MRWE Application Framework © 1997-2004 Absoft Corporation) was used for standardization and final data preparation for further correlation analysis (Cook and Holmes, 1986). Datasets consisting of young trees were detrended by applying negative exponential curves, and others were detrended using the smoothing spline (step length 100). Young and old trees might have such different trends on different time scales that different detrending methods were necessary in order to minimize the individual non-climatic signals (noise) and maximize the common climate signal in the young and old trees. The mean interseries correlations (Rbar), the expressed population signal (EPS) and other statistics were used in order to check the quality of our chronologies. For the statistics analysis the dendrochronology program library (dplR) was applied (Bunn, 2008). The EPS of 0.85 has been chosen as an appropriate criterion to ensure the reliability of our chronologies (Wigley et al., 1984). In order to maximize the high frequency signal the residual chronologies were chosen for correlation analysis, removing autocorrelation from the series using autoregressive modeling. Finally, adaptive power transformation was used to stabilize the variance (Cook and Peters, 1997). This was done in order to remove non-climatic variability, for example age-related growth trends and to reduce the noise caused by individual trees.

2.2 Climate setting and meteorological data

In analysis we used monthly and daily climate data obtained from the KNMI climate explorer (www.climexp.knmi.nl) (Trouet and Oldenbourgh, 2013) and from the USA

National Snow and Ice Data Center (NSIDC) (Table III–2). Databases we used include: the Global Historical Climatology Network (GHCN)-Daily v.2 database (Menne et al., 2012), Climate Research Unit (CRU) TS 4.00 (Harris et al., 2014) and Central Asia temperature and precipitation data, 1879-2003 (Williams and Konovalov, 2008).

We used data from the Almaty weather station (WMO number 36870) because it is the nearest station (straight-line distance to the sampling site is 17 km). In order to exclude the influence of different length of climate datasets on correlation results, we limited the length of all climate datasets and chronologies to the length of the minimal available period, from 1926 to 1982. Different climatic parameters were taken into consideration, including: precipitation, maximum, minimum and average temperature.

Drought was investigated using the Standardized Precipitation Evapotranspiration Index (SPEI). The SPEI is basically a difference between potential evapotranspiration (PET) and precipitation, so for instance 12-month SPEI is a difference between PET and precipitation accumulated over the 11 months before to the current month. We did analysis with all SPEI datasets available on the KNMI climate explorer, trying to find the best correlations.

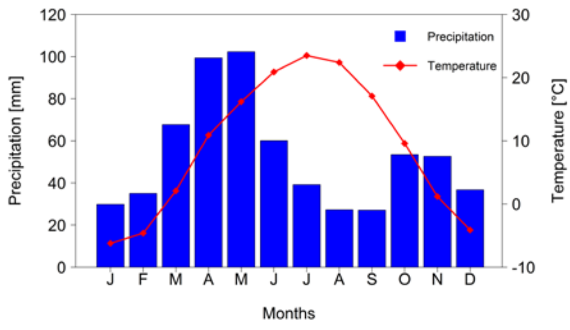
Table III-2: Climate data.

Climate data	Observation period	Coordinates	Climatic parameters	Data source
Almaty station (monthly data)	1926-1982	43.23 N, 76.93 E, 851 m a.s.l.	Precipitation; Average, Maximum and Minimum temperature	KNMI climate explorer and USA NSIDC
Almaty station (daily data)	1926-1982	43.23 N, 76.93 E, 851 m a.s.l.	Precipitation; Average, Maximum and Minimum temperature	KNMI climate explorer
Gridded data CRU TS 4.00	1926-1982	43.05 N, 76.45 E, 1973 m a.s.l.	Precipitation; Average, Maximum and Minimum temperature and SPEI	KNMI climate explorer

The climate in the region in general is characterized by strong seasonality in temperature with maximum in July and August, and bimodal precipitation regime, with two peaks, one in April-May and second in October-November (Figure III–2).

The mean annual air temperatures (MAAT) is around 9.1°C and mean annual precipitation totals are about620 mm, with fluctuations ranging from 570 to 710 mm during the period from 1894 to 2011.

Also we should mention that the bimodal precipitation regime recorded in Almaty is not so pronounced at higher elevations where we have just one peak from April to August instead of two.



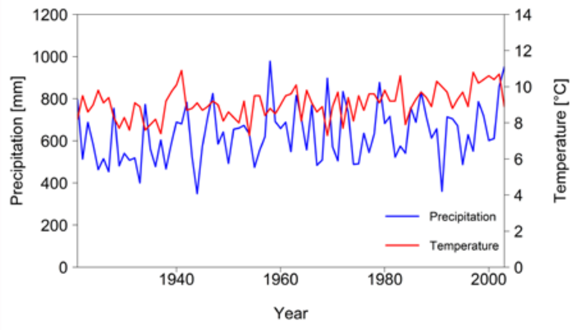


Figure III-2: Temperature and precipitation graphs for the period 1921-2003, left – monthly average, right – annual precipitation totals and MAAT, based on the Almaty weather station.

The temperature has an increasing trend and the rate became faster after 1982, whereas precipitation had a decreasing trend at the beginning of the last century, after that, the trend leveled and became a nearly flat line from 1958 to 2010 (Cherednichenko et al., 2015).

Monthly data correlations, including spatial correlations, were analyzed in the KNMI climate explorer, and daily data using the (CLIMTREG_V4) program (Beck et al., 2013). The CLIMTERG calculates correlations starting in July of the last year running to the end of October of the current year. The correlation starts with a 21 days window shifting every time by one day. After this the program starts calculation again but now with 22 days window. The process continues until reaching 121 days. In the end it presents the best correlation results which were found.

In order to check the temporal stability of the climatic signal, the running correlation with 30 years window and minimum number of years with data = 1 was applied. Spatial correlation analysis shows the geographic representation of our chronology. It was performed for the territory (35°-55°N, 45°E-95°E), which covers the whole Central Asia, northwestern China, western Mongolia and adjacent territories of Russia.

Climatic parameters investigated on spatial correlations include precipitation, average, minimum and maximum temperature and the SPEI. We checked correlations for both previous and current years, because growth in the current year can be affected by the precipitation and temperature conditions of previous year (Schweingruber, 1996).

3 Results

3.1 Chronologies and sensitivity

Three residual chronologies of EW, LW and TRW were built for each group of trees. In total, eight chronologies were taken into account for correlation analysis. Due to insufficient values of EPS and Rbar, LW chronology of young trees was excluded from the analysis (Figure III–3). All other chronologies demonstrate good quality and applicability for climate correlation analysis, for the period 1926-1982. Chronology statistics obtained from the ARSTAN program are presented in Table III–3. Data analysis revealed the differences in mean sensitivity among all datasets. In general the LW shows higher sensitivity. EW and TRW have more or less equal values that vary from 0.19 to 0.27. The intercorrelation between individual measurement series was lower for LW and higher for EW and TRW. Rather high values of the variance in the first eigenvector indicate similarity of signals reflected by each group of trees. In all cases, the highest value of mean sensitivity (MS) were found for young trees whereas old trees show the lowest values, which is interesting because contradicts the Borscheva's findings (Table III–3).

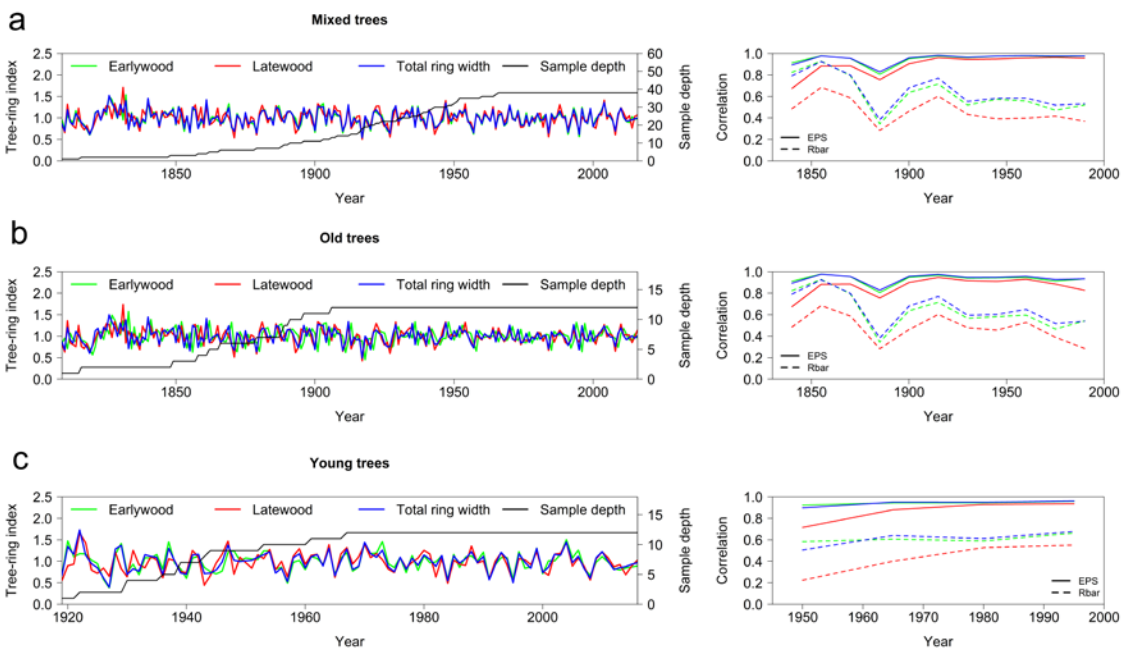


Figure III-3: Tree-ring residual chronologies and sample depth of all (a), old (b) and young (c) trees. EPS and Rbar statistics calculated over a 30-year period lagged by 15 years (right). Green line – EW, red line – LW and blue line – TRW.

Table III-3: Statistics for the residual chronologies.

Chronology	EW all	EW old	EW young	LW all	LW old	TRW all	TRW old	TRW young
Chronology time span	1808-2016	1808-2016	1919-2016	1808-2016	1808-2016	1808-2016	1808-2016	1919-2016
Common interval	1967-2016	1906-2016	1967-2016	1967-2016	1906-2016	1967-2016	1906-2016	1967-2016
Number of trees and radii	21 trees 38 radii	7 trees 12 radii	7 trees 12 radii	21 trees 38 radii	7 trees 12 radii	21 trees 38 radii	7 trees 12 radii	7 trees 12 radii
MS[a]	0.21	0.20	0.27	0.22	0.21	0.21	0.19	0.27
SD[b]	0.18	0.18	0.23	0.19	0.19	0.18	0.17	0.23
SNR[c]	29.10	9.49	13.16	16.66	6.81	32.00	11.24	14.50
1EV[d] (%)	58.09	59.00	67.39	42.77	48.59	60.74	63.38	70.78
Mean correlation between all series	0.53	0.53	0.61	0.36	0.42	0.55	0.57	0.64
EPS[e]	0.97	0.90	0.93	0.94	0.87	0.97	0.92	0.94

[a]MS Mean sensitivity

[b]SD Standard deviation

[c]SNR Signal-to-noise ratio

[d]1EV Variance in first eigenvector

[e]EPS Expressed population signal

Correlations are statistically significant (p<0.05)

3.2 Results of correlation analysis

Correlations between various tree-ring parameters and all age groups with daily climate data revealed stronger relationships than with monthly CRU data or monthly station data (Table III–4). The analysis revealed that the TRW better correlates with the SPEI 12; EW yielded the strongest correlation with precipitation and LW with temperature (Table III–5). Results of the running correlation analysis showed the temporal stability of precipitation and SPEI 12 signals. The correlation values vary from 0.6 (p<0.05) to 0.74 (p<0.001) and from 0.52 (p<0.01) to 0.74 (p<0.001), for precipitation and SPEI respectively. In contrast, the temperature signal showed gradual decreasing of correlation from 1926 to 1982 becoming insignificant after 1979 (Figure III–4). The correlation values vary from -0.76 (p<0.001) to -0.31 (p>0.2) for minimum temperature, from -0.8 (p<0.001) to -0.44 (p<0.05) for average temperature and from -0.76 (p<0.001) to -0.27 (p>0.3) for maximum temperature.

Table III-4: Strongest correlations between different climate datasets and chronologies of different age groups of trees. Precipitation correlated with EW, temperature with LW and the SPEI 12 with TRW (please note correlations increasing from left to right).

Climatic parameter	CRU TS 4.00 (only mixed trees)	CRU TS 4.00 (all groups)	Monthly station data (all groups)	Daily station data (all groups)
Precipitation	r = 0.348*** previous July	r = 0.368** July	r = 0.429*** October	r = 0.635** previous July 6th – November 3rd
Average temperature	r = -0.483*** July	r = -0.540* July	r = -0.574* July	r = -0.670*** June 11th – August 4th
Minimum temperature	r = -0.417*** July	r = -0.480* July	r = -0.495* July	r = -0.639*** June 11th – August 4th
Maximum temperature	r = -0.503*** July	r = -0.555* July	r = -0.573* July	r = -0.656*** June 25th – July 17th
SPEI 12	r = 0.53*** June	r = 0.614* June	n/a	n/a

*young trees **old trees ***mixed trees, correlations are statistically significant (p<0.05)

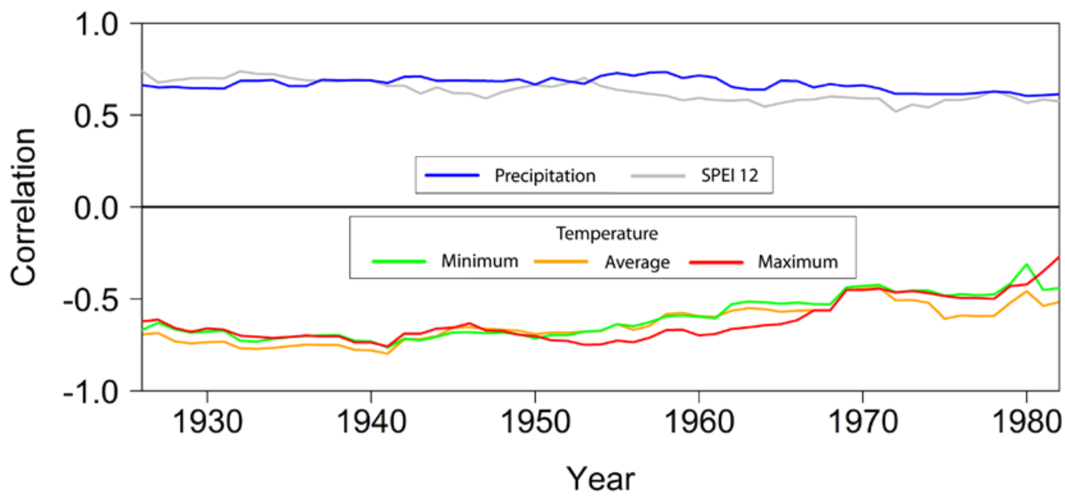


Figure III-4: The running correlation analysis (window size = 30 years, minimum number of years with data = 1). Correlation values for precipitation and SPEI 12 signals are significant during the entire observation period (p<0.05) and temperature signals are significant only until 1979.

Table III-5: Correlation results in the CLIMTREG, between daily climate data and different age groups and tree-ring parameters.

Tree-ring parameter	Climatic parameter	Young trees		Old trees		Mixed trees	
		Period	Number of days	Period	Number of days	Period	Number of days
EW	Precipitation	Previous July 6th – November 2nd	119	Previous July 6th – November 3rd	120	Previous July 6th – November 3rd	120
LW	Average temperature	June 11th – August 10th	60	June 23rd – July 16th	23	June 11th – August 4th	54
	Minimum temperature	June 10th – August 10th	59	June 23rd – July 20th	27	June 11th – August 4th	54
	Maximum temperature	June 25th – August 4th	40	June 23rd – July 16th	23	June 25th – July 17th	22
TRW	SPEI 12	June	-	June	-	June	-

3.3 Spatial correlation

The spatial correlation with different climatic parameters revealed that the best correlations are mainly associated with the territory of Kazakhstan, but some correlations are also found in the adjacent territories of Kyrgyzstan and China (Figure III–5). Correlations with temperatures show gradual changes whereas precipitation and drought have more heterogeneous patterns. The EW of old trees shows best correlation with precipitation, and TRW of young trees shows stronger and more precise correlation with the SPEI drought index. Spatial field correlations between temperature and old trees cover a smaller area compared to mixed trees, which cover a bigger territory stretching up to central Kazakhstan. Also it was noted that correlations with mixed dataset provides better results compared to old and young trees separately (Figure III–6).

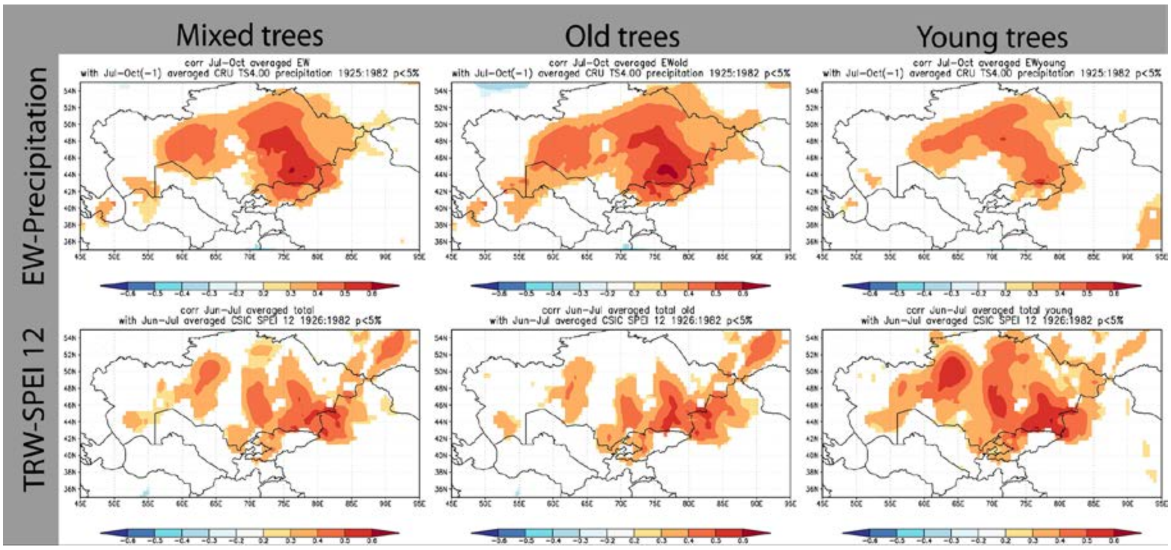


Figure III-5: The spatial correlation analysis with CRU TS 4.00 datasets (precipitation and SPEI 12), for the period 1926-1982. Correlations are statistically significant (p<0.05).

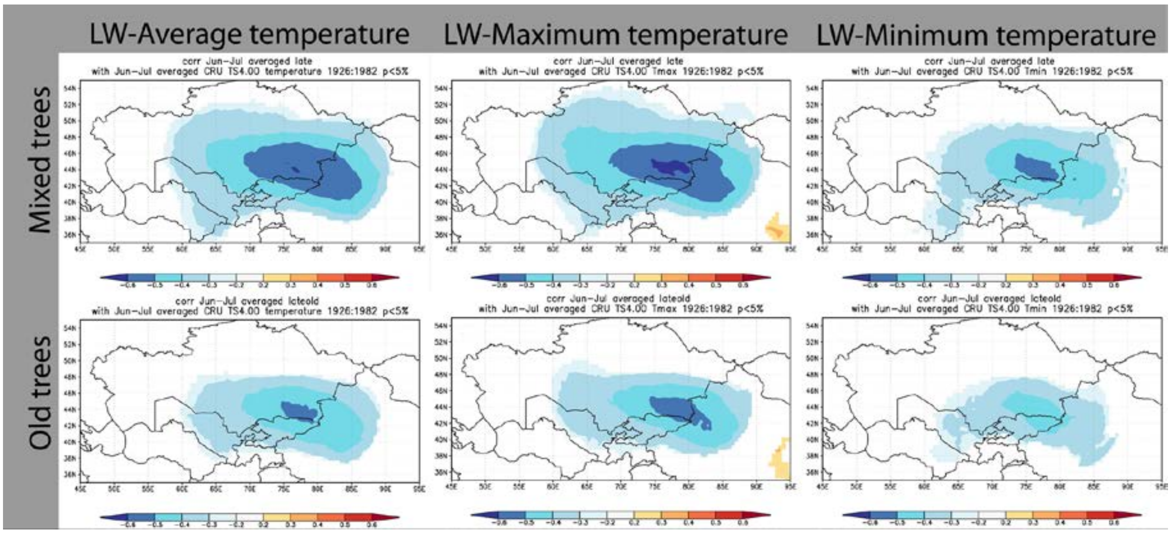


Figure III-6: The spatial correlation analysis with CRU TS 4.00 datasets (average, minimum and maximum temperature), for the period 1926-1982. Correlations are statistically significant (p<0.05).

4 Discussion

The weak statistical results of the LW chronology of young trees can be due to so called “Divergence Problem” and associated with reduction of sensitivity and changes in the structure of temperature signal in radial tree growth since the middle 20th century (D’Arrigo et al., 2008). This assumption is also supported by our running correlation analysis, which showed the decreasing of the temperature signal. Higher values of MS and the variance in the first eigenvector for young trees indicate higher dependence on environmental conditions compared to old trees. These results are also in agreement with the results reported in Wu et al. (2013). According to Borscheva (1983) differences in sensitivity between trees of different age are connected to critical periods of ontogenesis, middle age trees are characterized by intensive seeding which make them more sensitive to environmental changes. This could be the reason why our young trees showed higher MS compared to old trees. The ratio between latewood and earlywood also has direct connections to sensitivity, the more the latewood content the higher the sensitivity (Borscheva 1986).

Young trees show higher sensitivity to drought conditions compared to old trees since this is a limiting factor, which determines the vegetation period for them. Old trees in contrast, have ample sunlight, fully developed root systems that assists in drought tolerance, but they are more sensitive to the availability of water resources (Kozhevnikova, 1981). The common period when drought affects both age groups is current June-July. Correlations with temperatures in current July, especially with maximum temperature is also in agreement with Borscheva's results (1983) which showed that, in July LW formation starts and we see that temperature has the primal effect on this process. Negative correlations with temperature in July are also in agreement with results published by Magnuszewski et al. (2015). It can be also considered as a manifestation of drought stress, because low precipitation and high temperature can affect the production of sugars (LaMarche 1974). The LW formation of old and young trees, which is driven by temperature characteristics, starts and ends in different time periods. Hence, if we do seasonal averaging, we should use mixed datasets, since it can cover the whole period of LW formation and better reflects temperature changes. Such age-dependent differences in climatic sensitivity were reported for various tree species (Vieira et al., 2009; Yu et al., 2008; Wang et al., 2009; Rozas et al., 2009). There are many explanations why this difference exists, for example variations in the period of xylem growth (Rossi et al., 2008), lower photosynthetic rates in older trees (Bond, 2000), or increasing of hydraulic resistance (Carrer and Urbinati, 2004).

Another interesting fact was a shifting of strongest correlations values for precipitation. The CRU data demonstrate highest values between EW and precipitation in previous July, whereas station data showed strongest correlation with precipitation in previous October. This shifting probably can be explained by differences in altitude between station and sampling site and also by some orographic features. In general the highest correlations were found in the period from previous July to previous November. This shows that the previous year affects the content of EW, and wet conditions are beneficial for trees, because this reduces evapotranspiration and helps to save moisture for the next vegetation period which is also in agreement of results reported by Chen et al. (2017)

The spatial correlations demonstrated a significant influence of orography and difference in precipitation regime. The Terskey Alatau and the Kungey Alatau located further to the East and the South from our sampling site are closed for entrance of northern and northwestern air masses (Aizen et al., 1997; Bolch, 2007). This probably explains a difference in reaction of Schrenk spruce in northern and central Tian Shan, when MS grows with altitude in the Trans-Ili Alatau (Roldugin, 1970; Kolov et al., 2003), but decreases in the central Tian Shan in China (Wang et al., 2005). Spatial correlations again demonstrated that each age group of trees captures specific signals and combined into a mixed dataset they provide better results. However a considerable amount of uncertainty still remains regarding what are the physiological reasons of differences in climatic sensitivity between old and young trees of Schrenk spruce in northern Tian Shan. Therefore further efforts are required in order to clarify this question.

Our results support our hypothesis. In all tests with daily climate data EW and LW provide strongest correlations with precipitation and temperature respectively. We see the obvious potential of using various tree-ring parameters of Schrenk spruce, for example in future dendroclimatic studies, since this gives a possibility to reconstruct several climatic parameters using the same trees each time.

5 Conclusion

We investigated how different combinations of climatic and tree rings datasets affect correlation results based on data collected in the southeastern part of Kazakhstan. For the first time, correlations between EW, LW and daily climate data for Schrenk spruce in the Trans-Ili Alatau (northern Tian Shan) were investigated.

Results indicate EW correlates most strongly with precipitation, LW responds best to temperature, and total ring width is mainly drought sensitive. Analysis using daily climate data demonstrated its perspective, providing better correlation values and more precise time intervals. Old trees yield better correlation results with precipitation. Mixed trees demonstrate best results with temperature and drought records. A shifting of strongest correlations in time was found, between EW and precipitation, when we use CRU data and station data. All this indicates the importance, of taking into consideration, which climate datasets, tree-ring parameters and age group we use in dendroclimatic research, because these have direct influence on correlation results.

This study is a small step towards understanding the relationships between climate conditions and spruce forest growth in Southeast Kazakhstan. In order to increase reliability of the analysis more samples need to be collected, therefore this study presents just a preliminary results. Moreover, based upon our findings it is possible that trees in the middle and upper forest belts may also show varying climate-growth relationships depending upon age class. Implementation of new methods like stable isotope and wood anatomy analysis can provide additional climatic information and complement ring width analyses.

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Chapter IV:
Variability of climate-growth relationships of Schrenk spruce (Picea schrenkiana Fisch. et Mey) in the Ile River basin (northern Tien Shan Mountains)

Regional Environmental Change (in review)

Bulat Zubairov, Karl-Uwe Heußner, Jan Lentschke and Hilmar Schröder

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Abstract

The tree growth is affected by different factors, including anthropogenic influence, climatic changes, orography, etc. In this study we examine spatiotemporal patterns of climate-growth relationships of Schrenk spruce, using samples collected in the Ile River basin (northern Tien Shan Mountains). We have developed 8 chronologies spanning 115 to 328 years. Correlation analysis suggests different influence of previous and current year climatic conditions on earlywood (EW), latewood (LW) and total ring width (TRW) growth. All developed chronologies showed the best correlations with the precipitation and the Standardized Precipitation-Evapotranspiration Index (SPEI), whereas temperature signal showed reduction starting from 1960s-1980s. Certain extreme years were revealed in 1879, 1885, 1890, 1917, 1918, 1925, 1927, 1937 and 1959 in the Terskey Alatau Mountains, in 1951, 1954, 1955 and 2008 in the Zhetysu Alatau Mountains and in 1882, 1879, 1892, 1894, 1897, 1932, 1941 and 1946 in the Kungey Alatau Mountains. The Morlet wavelet analysis indicates existence of high-frequency (~2-3, 2-4 years) and decadal scale (~11, 20, 60 years) periodicities in tree-ring growth. This study provides new information on climate-growth relationships of Schrenk spruce in mountain areas of the Ile River basin and contributes to development of the Central Asia tree-ring network.

1 Introduction

It is projected that the 21st century will bring significant changes in functioning of ecosystems worldwide due to climate change (Garcia et al. 2014; Pecl et al., 2017). Moreover, already in the 20th century a profound impact of climate change was noted, in particular in redistribution of climatic drivers of tree growth (Babst et al., 2019). Some regions, including the Central Asia region are projected to exhibit an amplified climatic response (Seddon et al., 2016). In addition to climate change induced threats, forests in Central Asia are also affected by such destructive phenomena as overgrazing, overharvesting and forest degradation from excessive recreation use, which brings additional pressures and interfere with natural forest renewal (Kushlin et al., 2003). Particular attention should be paid to the high-mountain areas, which are expected to be more vulnerable, because of more rapid temperature changes compared to environments at lower elevations (Mountain Research Initiative EDW Working Group 2015). The Tien Shan Mountains is one of them. It is one of the largest mountain systems in the Central Asia region with a total area around 800 000 km2 and located between 69°-95°E and 39°-46°N (Aizen et al., 1997). One of the dominant tree species here is the Schrenk spruce (Picea schrenkiana Fisch. et Mey). A number of dendroclimatic studies on Schrenk spruce, investigated climatic signals along an altitudinal gradient, age-dependent tree-ring growth and treeline dynamics in response to climatic variability, have already been published (Wang et al., 2005; Wang et al., 2006; Wu et al., 2013). Currently, such kinds of studies have most actively been conducted in the central, eastern and southern parts of the Tien Shan Mountains. In turn, in the northern part, particularly in the Ile River basin, such investigations have been just recently resumed, after a long break associated with the collapse of the Soviet Union (Zubairov et al., 2019). According to analysis presented in the National Strategy and Action Plan on Sustainable Development of Kazakhstan Mountain Territories, during the period 1964-1984 a steady reduction in the area of forests and shrubs and the renewal of coniferous forests was revealed. For example during the period 1960-1990 the wild apple habitat reduced by 30% in the Zhetysu Alatau and by 60% in the Ile Alatau (National Academy of Sciences of the Republic of Kazakhstan, 2001). At the same time, the fact that the data are given for sparsely populated areas indicates low anthropogenic influence and high value of climatic factors. For a more accurate assessment of changes in the functioning and dynamics of Schrenk spruce forests in the Ile River basin and for better understanding of possible future effects, additional information is of high importance. Therefore, new extensive dendroclimatic studies are required. In this study we present new data on spatiotemporal variability of climate-growth relationships of Schrenk spruce in the three least studied mountain areas of the Ile River basin.

2 Data and methods

2.1 Study areas

Our study focuses on three mountain ranges, in the Ile River basin (northern Tien Shan): the Terskey Alatau, the Zhetysu Alatau (Dzhungar Alatau or Jungar Alatau) and the Kungey Alatau. These mountain ranges are formed by the Proterozoic and Paleozoic strongly dislocating terrigenous, effusive and metamorphic rocks and granite intrusions (Akzhygitova et al., 2003). All three are stretched in latitudinal direction and have maximum elevations above 4000 m a.s.l. (Iskakov and Medeu, 2007; Dimeyeva et al., 2016). Regionally they are belong to the so called Dzungar-North Tien Shan group of vegetation altitudinal zonality types, which consist of five belts and subbelts of vegetation types. The lowest belt – is steeps, followed by the belt of dark coniferous forests and meadows. Higher up is the belt of subalpine-like meadows and juniper elfin woods. The next one is the cryophytic (alpine-like) meadows and communities of Kobresia. The one on top is the subnival belt (Akzhygitova et al., 2003). The dominant tree species here is the Schrenk spruce (Picea schrenkiana Fisch. et Mey). It grows at elevations from 1400 to 3600 m a.s.l., but the ecological optimum is located at elevations from 2000 to 2500 m a.s.l. where the mean annual air temperatures (MAAT) ranges from -2 to +2 °C and the amount of precipitation ranging from 500 to 700 mm. The Schrenk spruce can grow up to 40-50 m in height, up to 1-1.5 m in diameter and has an average lifespan of 200-300 years (Borscheva 1983; Solomina et al. 2012).

2.2 Tree-ring data

Our first sampling site was located in the southern part of the Zhetysu Alatau, in the Tyshkan gorge (TSK); the second was located in the Kungey Alatau, in the Kolsay gorge (KOL) and the last one in the Terskey Alatau, in the Bolshoy Kokpak (BKP) gorge (Figure IV–1). Samples were collected at elevations from 2150 to 2300 m a.s.l., on the northern and northwestern slopes, characterized by the thin soil layer, and inclination ranging from 20° to 35°. In total we collected 102 Schrenk spruce samples from 63 trees.

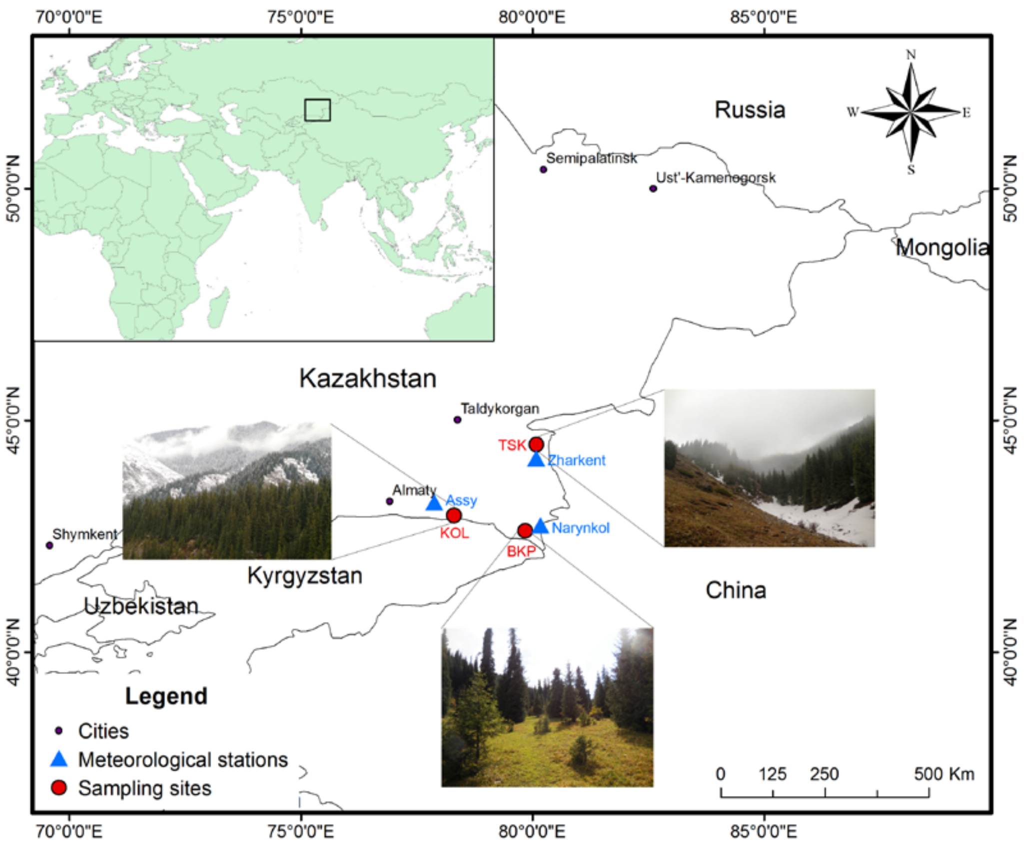

Figure IV-1: Study region and photos from the sampling sites. Red circles mark sampling sites KOL – Kolsay (the Kungey Alatau), BKP – Bolshoy Kokpak (the Terskey Alatau), TSK – Tyshkan (the Zhetysu Alatau). Blue triangles mark closest meteorological stations.

For sampling we tried to choose healthy trees, without signs of diseases and injury, in order to minimize non-climatic effects on radial growth. For most sampled trees, we collected two cores, from different directions at two flanks of a given tree, parallel to the slope, at breast height according to the standard procedure outlined in Speer (2010). All collected samples were mounted and polished with progressively finer sandpaper. Then the prepared samples were scanned at 1200 dpi and measured, using the WinDENDRO semi-automatic system (Regent Instruments Canada Inc., 2009). In this system, tree rings are automatically detected based on light intensity differences and then visually checked on presence of missed/false rings and misclassifications.

The obtained measurements for TRW, EW and LW were then visually cross-dated in the TSAPWin program (Time Series Analysis and Presentation for Dendrochronology and Related Applications; version 4.67c © 2002-2011 Rinntech), then cross-dating was verified using the COFECHA program (Version 6.06P © 1997-2004 Absoft Corporation) and corrected whenever it was necessary (Holmes, 1983).

We have developed tree-ring index chronologies, using the standardization technique in the ARSTAN program (AutoRegressive STANdardization; MRWE Application Framework © Absoft Corporation) (Cook and Holmes, 1986). In order to eliminate age related and other non-climatic trends in our tree-ring width series, we detrended them by applying a cubic smoothing spline with frequency response 0.5 at a wavelength of two-thirds the sample series length (Cook and Peters, 1981). We stabilized the variance using the r-bar weighted method (Cook and Krusic, 2011) and applied a robust bi-weight mean to develop final indexed chronologies (Cook, 1985; Cook et al., 1990).

The Expressed Population Signal (EPS), the mean inter-series correlations (Rbar) and other statistics were calculated in order to check the quality of our chronologies. The EPS was calculated in 30-year intervals with 15-year overlaps in order to determine a common period for the individual chronologies. The EPS provides estimates of how well a chronology of a particular sample size represents the population growth signal in a theoretical infinite population (Wigley et al., 1984). The widely used EPS-threshold of 0.85 has been chosen as an appropriate criterion to ensure the reliability of our chronologies. For correlation analysis the residual chronologies were chosen, in order to maximize the high frequency signal. The basic statistics for chronologies, including mean sensitivity (MS), signal-to-noise ratio (SNR) as well as the Morlet wavelet analysis were obtained using dendrochronology program library (dplR) (Bunn, 2008).

2.3 Meteorological data

The closest meteorological stations (Zharkent, Assy, Narynkol) are located from 30 to 50 km away and either 500-1500 m lower or 500-600 m higher than our sampling sites (Figure IV–1). Additionally, instrumental observation data from these stations are relatively short (30-40 years) and often show significant gaps. Therefore, for analysis we used monthly climate database the Climate Research Unit (CRU) TS (Time-Series) 4.02 (Harris et al., 2014). Gridded (0.5° × 0.5°) data, including: the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), precipitation, mean maximum, mean minimum and mean temperature were obtained from the KNMI climate explorer (https://climexp.knmi.nl) (Trouet and Oldenborgh, 2013) (Table IV–1).

Table IV-1: Climate data.

Climate data	Coordinates	Climatic parameters	Observation period (years)	Data source
Gridded (0.5° × 0.5°) data CRU TS 4.02	BKP (42.37N, 79.50E) KOL (42.57N, 78.18E) TSK (44.29N, 80.05E)	Mean minimum, mean maximum, Mean temperature and precipitation (monthly)	117 (1901-2017)	KNMI climate explorer
		SPEI (monthly)	113 (1901-2013)	

Climate conditions at the sites are characterized in general by strong seasonal changes in temperature with maximum in July and August. The precipitation regime at the TSK study area is bimodal with two peaks, the first in May-July and the second in October-November. The amount of precipitation during these periods in average accounts for 50-55% of annual total precipitation. At the BKP and the KOL study areas the precipitation regime is different. It has just one peak in May-July and amount of precipitation in this period in average accounts for 40-45% of annual total precipitation. At the BKP study area climate is cooler and amount of precipitation is a little bit smaller compared to other sites, which can be explained by certain features of precipitation regime and orography. During the period from 1901 to 2017 climate at the sites exhibits a wetting-warming trend with amplitudes of 3.8, 4.9 and 5.3 mm/10a at the BKP, the KOL and the TSK respectively and 0.17 °C/10a at all three sites (Figure IV–2). The most noticeable increase of temperature occurred in winter – spring period from January to April and from October to December.

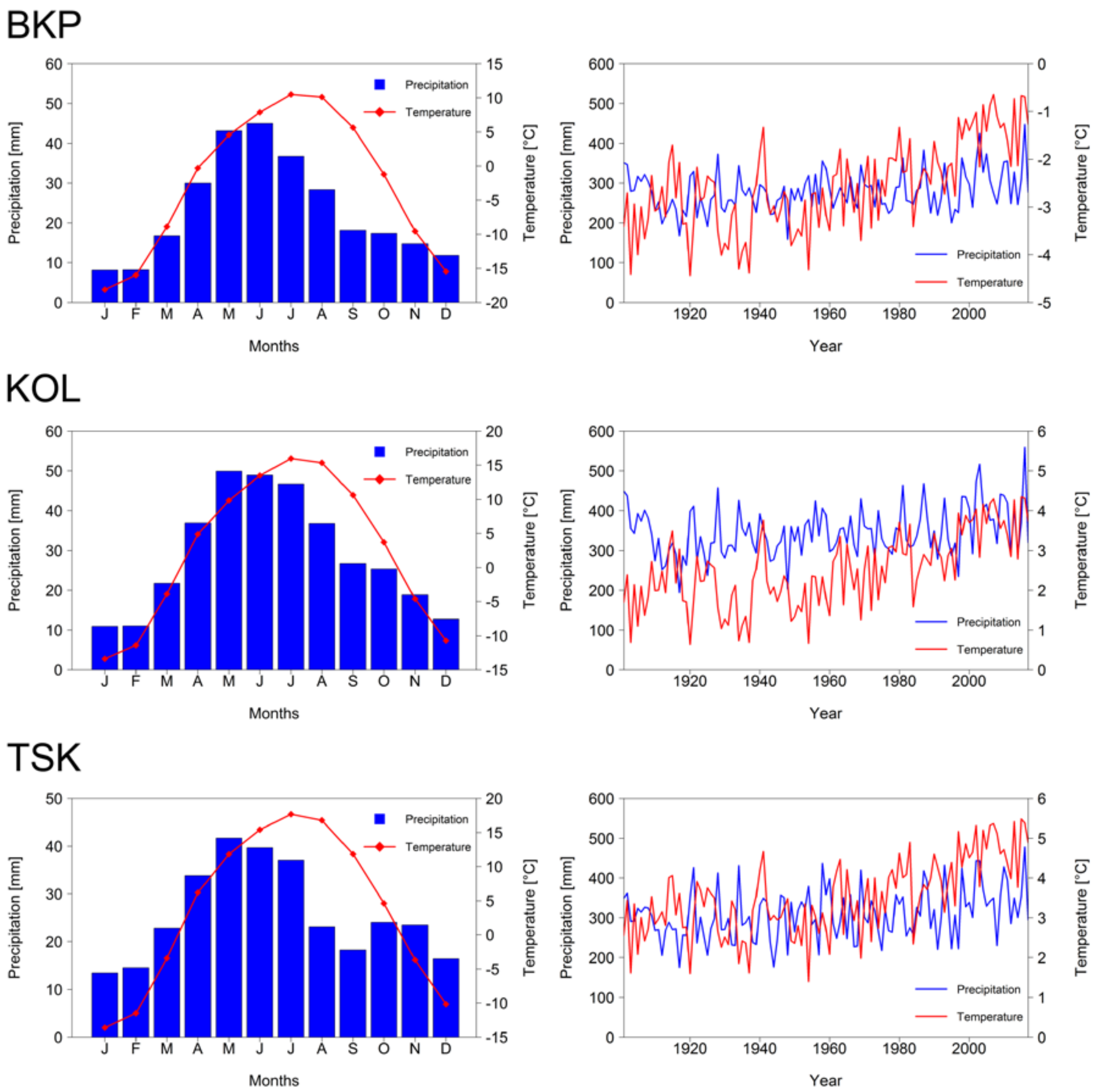

Figure IV-2: Precipitation and temperature graphs for the period 1901-2017, left – monthly average, right – annual precipitation totals and MAAT, based on CRU TS 4.00.

2.4 Data analysis

The preliminary results for the BKP_TRW chronology were obtained from the study by Zubairov et al. (2018a). In order to indicate climate-growth relationships for other 7 chronologies, simple correlation was calculated. Correlation analyses were performed both for previous and current years, because tree growth can be affected by climatic conditions of previous years (Schweingruber, 1996). The strongest correlations were investigated on temporal stability by applying the running correlation with 31 years window and minimum number of years with data = 1. The spatial correlation analysis was applied in order to show the geographic representation of our chronologies. It was performed for the territory (30°-60°N, 40°-100°E), which covers adjacent territories of Russia, western Mongolia, northwestern China and the entire Central Asia. Variations in tree-ring indices (TRI) were investigated by applying a 15-years low-pass filter. Finally, the Morlet wavelet analysis was performed in order to investigate the periodicity in our series and to examine temporal periodicity changes (Torrence and Compo, 1998).

3 Results

3.1 Chronologies

From a total of 102 collected samples, 6 were removed due to low correlation between the master series and the subseries, which probably occurred as a result of the high number of individual abnormalities. As the result, 26 cores from 15 trees at the KOL, 35 cores from 20 trees at the BKP and 35 cores from 25 trees at the TSK sites were used for chronologies development. In total we obtained 9 chronologies (the EW, the LW and the TRW chronology for each of three sites). Unfortunately, the LW chronology from the KOL study area was excluded due to insufficient values of EPS and Rbar (Figure IV–3).

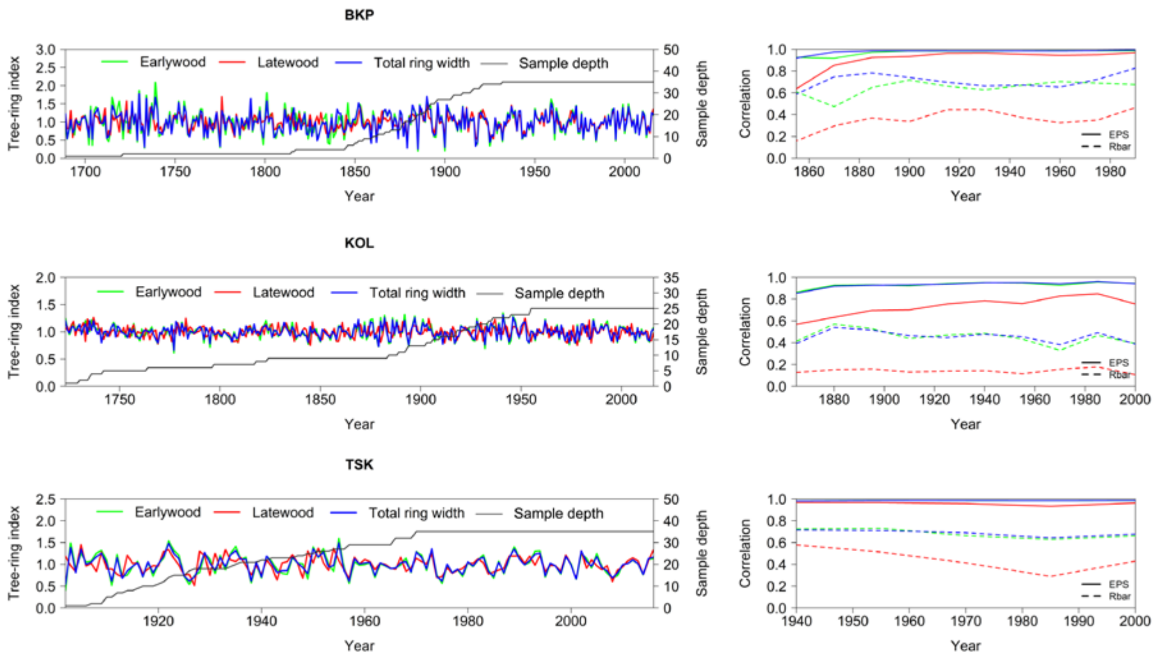

Figure IV-3: Tree-ring residual chronologies and sample depth (left). EPS and Rbar statistics calculated over a 30-year period lagged by 15 years (right).

In general, LW chronologies of all three sites had lower statistical characteristics and higher number of missing and false rings compared to the EW and the TRW chronologies. The highest mean sensitivity (MS) was demonstrated by the BKP chronology. Incidentally, it is also the longest running chronology (328 years) (Table IV–2).

Table IV-2: Chronologies statistics.

Chronology	BKP_ TRW	BKP_ EW	BKP_ LW	KOL_ TRW	KOL_ EW	TSK_ TRW	TSK_ EW	TSK_ LW
Coordinates	42.37°N-79.50°E, 2235 m a.s.l.			42.57°N-78.18°E, 2302 m a.s.l.		44.29°N-80.05°E, 2142 m a.s.l.		
Location	B. Kokpak			Kolsay		Tyshkan		
Number of trees and radii	trees-20, radii-35			trees-15, radii-26		trees-25, radii-35		
Span and length, years	1689-2016, 328			1723-2016, 294		1902-2016, 115		
First year of EPS[e]>0.85	1855		1870	1865		1940		
SD[b]	0.285	0.319	0.216	0.108	0.124	0.208	0.236	0.19
MS[a]	0.347	0.381	0.26	0.121	0.136	0.242	0.273	0.207
SNR[c]	24.622	20.186	8.165	7.932	7.802	28.167	25.288	11.492
Mean correlation between all series	0.683	0.641	0.4	0.4	0.388	0.6	0.576	0.365
Correlations within trees	0.845	0.816	0.594	0.596	0.514	0.769	0.76	0.552
Correlations between trees	0.679	0.673	0.395	0.393	0.386	0.595	0.571	0.36

[a]MS Mean sensitivity

[b]SD Standard deviation

[c]SNR Signal-to-noise ratio

[e]EPS Expressed population signal

Correlations are statistically significant ($p<0.05$)

3.2 Schrenk spruce growth response to climate

The correlation analysis revealed that Schrenk spruce growth is mainly dependent on humidification conditions. Strong positive correlations were revealed with precipitation and SPEI03 in previous summer-autumn and current late spring-summer periods. In turn, correlations with temperature mostly showed negative and lower values. The common for all three sites, and statistically significant correlation period with temperature, was revealed in previous July-August. Also, we can note that climatic conditions in previous and current years are exhibit relatively equal influence on EW, LW and TRW growth at the BKP site, whereas at the TSK site LW growth is primarily driven by climatic conditions in current year and EW and TRW growth by conditions in previous year (Figure SM IV–1).

The greatest effect of temperature on the tree-ring growth was revealed at the TSK study area. The strongest correlations with mean and mean maximum temperature for EW and

TRW here is vary from -0.43 to -0.52, whereas at the other sites it in general vary from -0.22 to -0.36. However, the correlation period (previous July-August) is common for all three sites. In turn the influence of humidification conditions is more diverse. The strongest correlations again were revealed at the TSK site and vary from 0.5 to 0.55 and from 0.48 to 0.55 for the precipitation and the SPEI03 respectively. At the other sites correlations in general vary from 0.33 to 0.43.

The main difference was found in the correlation periods. The longest correlation period (current February-July) was between the BKP_TRW and precipitation and the shortest one between the KOL_TRW and precipitation (previous July-September). Additionally, strongest correlations between precipitation, the BKP_TRW and the BKP_EW were revealed for current year, whereas at the other sites they revealed for previous year. Meanwhile the LW showed strongest correlations with precipitation in previous years at the BKP site and with the current year at the TSK site. A similar situation was observed with the SPEI03 data (Table IV–3).

Table IV-3: Strongest correlations between the chronologies and climate.

	BKP			TSK			KOL	
	TRW	EW	LW	TRW	EW	LW	TRW	EW
Precipitation	current Feb-Jul (r=0.41, *p*<0.0001, n=116)	current May-Jul (r=0.40, *p*<0.0001, n=116)	previous Jul-Nov (r=0.43, *p*<0.0001, n=117)	previous Jun-Oct (r=0.50, *p*<0.0001, n=76)	previous Jun-Sep (r=0.54, *p*<0.0001, n=76)	current Jun-Aug (r=0.55, *p*<0.0001, n=77)	previous Jul-Sep (r=0.42, *p*<0.0001, n=115)	previous Jul-Sep (r=0.41, *p*<0.0001, n=115)
Mean maximum temperature	previous Jul-Aug (r=-0.36, *p*<0.001, n=115)	previous Jul-Aug (r=-0.34, *p*<0.001, n=115)	previous Jul-Sep (r = -0.33, *p*<0.001, n=115)	previous Jul-Sep (r = -0.49, *p*<0.0001, n=76)	previous Jul-Sep (r=-0.52, *p*<0.0001, n=76)	current Jul (r=-0.36, *p*<0.01, n=77)	previous Jul-Sep (r=-0.35, *p*<0.001, n=115)	previous Jul-Sep (r=-0.36, *p*<0.001, n=115)
Mean temperature	previous Jul-Aug (r=-0.33, *p*<0.001, n=115)	previous Jul-Aug (r=-0.30, *p*<0.01, n=115)	previous Jul-Aug (r=-0.29, *p*<0.01, n=115)	previous Jul (r=-0.43, *p*<0.001, n=76)	previous Jul (r=-0.47, *p*<0.0001, n=76)	current Jul (r=-0.35, *p*<0.01, n=77)	previous Jul-Sep (r=-0.33, *p*<0.01, n=115)	previous Jul-Sep (r=-0.34, *p*<0.01, n=115)
Mean minimum temperature	previous Jul (r=-0.24, *p*<0.01, n=115)	previous Jul (r=-0.22, *p*<0.05, n=115)	previous Jul-Aug (r=-0.22, *p*<0.05, n=115)	previous Jul (r=-0.36, *p*<0.01, n=76)	previous Jul (r=-0.41, *p*<0.001, n=76)	previous Apr (r=-0.31, *p*<0.01, n=76)	previous Jul-Sep (r=-0.26, *p*<0.05, n=115)	previous Jul-Sep (r=-0.27, *p*<0.05, n=115)
SPEI 03	current Mar-Jul (r=0.34, *p*<0.001, n=113)	current Mar-Aug (r=0.34, *p*<0.001, n=113)	previous Sep (r=0.33, *p*<0.001, n=112)	previous Aug-Sep (r=0.52, *p*<0.0001, n=73)	previous Aug-Sep (r=0.55, *p*<0.0001, n=73)	current Jun-Sep (r=0.48, *p*<0.0001, n=74)	previous Sep (r=0.42, *p*<0.0001, n=112)	previous Sep (r=0.39, *p*<0.0001, n=112)

3.3 Running and spatial correlation analyses

The strongest climatic signals were subjected to the running correlation analysis, in order to reveal temporal variations of correlations. Our analysis showed a temperature decrease signal starting from 1980s at the BKP and TSK sites and even earlier, from 1960s at the KOL site.

Meanwhile the SPEI and precipitation signals in general showed either relative stability or increasing of correlations. However, some decreasing of correlations was noted as early as in the 1960s at the KOL site, in the middle of the 1980s at the BKP site and in the early 1980s for the LW at the TSK site (Figure SM IV–2).

The spatial correlation analysis showed that TRW and EW in general have stronger correlations, which additionally covers bigger territory compared to LW. The correlations are mainly associated with the southeastern and central parts of Kazakhstan and adjacent territories of China, Kyrgyzstan and Uzbekistan. The lowest correlations were revealed with the mean minimum temperature. In addition, significant positive correlations associated with the territory of East European Plain were revealed for the KOL_TRW, the KOL_EW, the TSK_TRW and the TSK_EW chronologies (Figure SM IV–3, Figure SM IV–4, Figure SM IV–5).

3.4 Extreme years and periodicities

The lowest number of extreme years (± 2σ) was revealed for the TSK chronologies. Also, only at this site extreme years have occurred during the last 60 years, in 1975 for EW and in 2008 for LW. In general, extreme years do not coincide, only the BKP and the KOL chronologies have one common extreme year in 1879 (Figure SM IV–6). Additionally, the BKP chronologies showed higher number of extreme negative years, whereas for the KOL chronologies it is vice versa. Finally, we can note that at all three sites show at least some differences in extreme years between the EW, the LW and the TRW chronologies (Table IV–4).

The Morlet wavelet analysis also revealed certain differences in the temporal characteristics of the different periodicities. High-frequency cycles ~2-3, 2-4 years were found in all 8 chronologies. The BKP chronologies revealed cycles of ~4-9, 7-11 and 11-13 years during the periods 1850-1930, ~15-20 years cycle in the middle of XIX and XX centuries and ~50-60 years cycle for the LW chronology in the middle of XX century.

The TSK chronologies, in addition to ~2-4 years cycle revealed ~8-14 and 16-20 years cycles during the period from 1970s to 2000s and our KOL chronologies revealed ~4-8 and 50-60 year cycles during the periods from 1870s to 1900s and from 1920s to 1960s (Figure SM IV–7).

Table IV-4: Extreme years and periodicities.

	BKP			TSK			KOL	
	TRW	EW	LW	TRW	EW	LW	TRW	EW
Extreme positive years (+2σ)	1890	1890, 1959	1890, 1937	1955	1955	1951, 1955	1882, 1941, 1946	1882, 1892, 1897, 1941
Extreme negative years (-2σ)	1879, 1885, 1900, 1917	1879, 1885, 1900, 1917, 1925	1879, 1885, 1917, 1927	-	1975	2008	1879, 1894	1932
Periodicities	2-4, 4-9, 7-11, 15-20	2-4, 4-9, 7-11, 15-20	2-4, 4-9, 11-13, 15-20, 50-60	2-4, 8-14, 16-20	2-4, 8-14, 16-20	2-5, 8-14	2-3, 4-8, 50-60	2-3, 4-8, 12, 50-60

Application of 15-years low-pass filter helped us to investigate the periods of increasing and decreasing of the TRI. Firstly, we discovered more frequent alternation of these periods for the BKP and the TSK chronologies compared to the KOL chronologies.

At the same time the variations are more consistent between the BKP and the KOL chronologies. For example, at the KOL and the BKP sites, in the period from 1940 to 2010, the trend has changed 5 times, whereas at the TSK site it has changed 12 times.

However, despite these differences, certain congruencies are also present. For example, the beginning of XXI century at all three sites marks a decrease of tree-ring growth. Another notable decrease of growth during the period from 1960s to 1970 is common for both the BKP and the TSK sites. In turn, the period from 1925 to 1940 marked the beginning of favorable growth conditions at the KOL and the BKP sites (Figure IV–4).

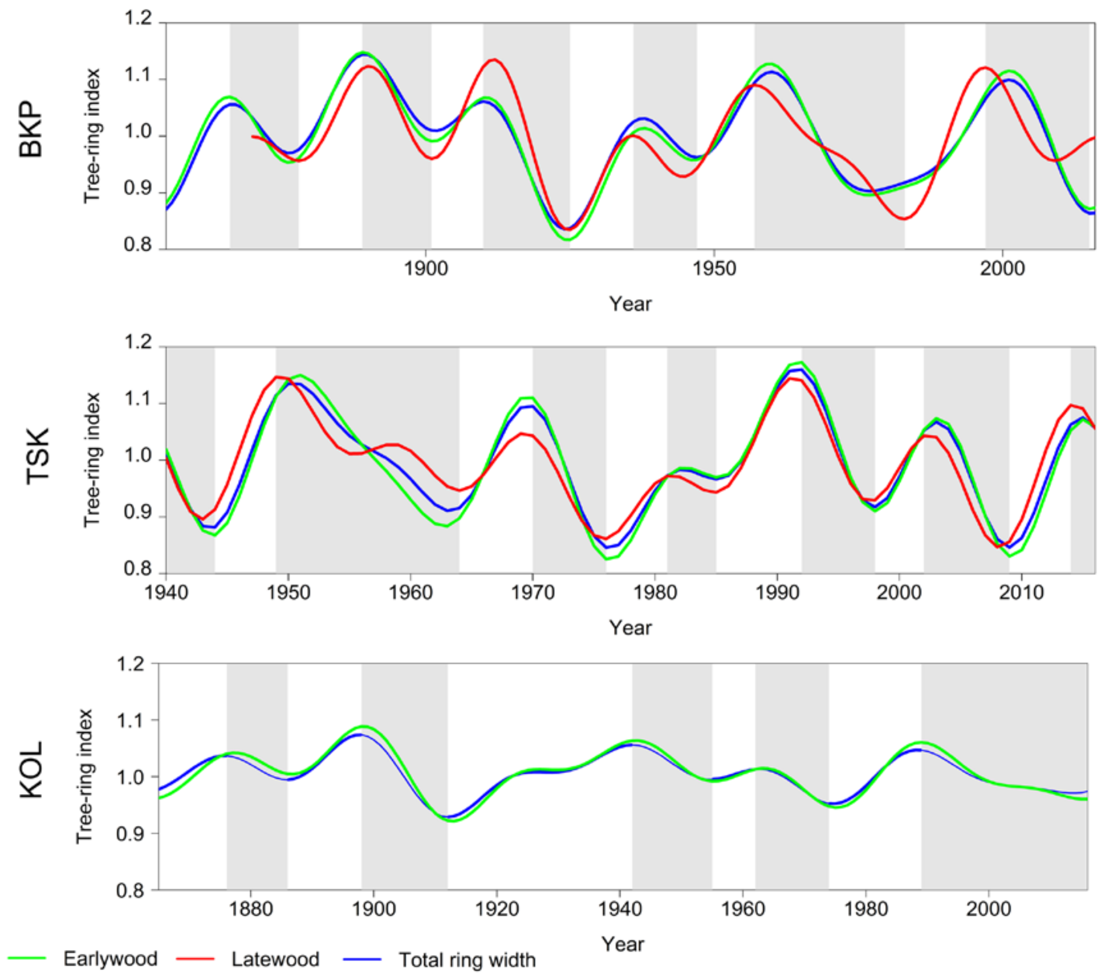

Figure IV-4: Variability of periods of increase and decrease in TRI, illustrated by the 15-years low-pass filter.

4 Discussion

Vegetation periods, the onset and duration of certain phases of plant development are not always the same. Within a certain climate and a genetically determined reaction rate, vegetation rhythms may depend on the influence of humans and animals (Larcher 1978). Therefore, revealed correlation periods with climate data explain phenology of Schrenk spruce in relatively approximate form, nevertheless allow certain conclusions to be drawn. Differences in temperature and precipitation regime in different parts of the Ile River basin have significant influence on climate-growth relationships of Schrenk spruce. Stronger dependence of tree growth from previous year precipitation in the Zhetysu Alatau Mountains compared to the Terskey Alatau Mountains is probably connected with dryer climate conditions. The average amount of precipitation at both sites is almost equal, whereas the MAAT in the Zhetysu Alatau Mountains is much higher. As results we have a faster decrease of soil water content and enhanced evapotranspiration. This in turn reduces photosynthesis, stomatal conductance and can affect the production of sugars (LaMarche 1974; Yin et al., 2008; Lévesque et al. 2013). Previous year precipitation enhances soil moisture storage, reducing evapotranspiration which is important for the upcoming vegetation year. In addition to direct growth-controlling factors we have other ones such as orography, soil characteristics and etc. These factors also have a strong influence through the redistribution of heat, moisture and nutrient. For example, in the Terskey Alatau Mountains, temperatures are lower because it is located in a deep and narrow gorge and therefore tree growth here is less dependent on humidification conditions. Similar effects have previously been observed by Borscheva in the Kungey Alatau Mountains (Borscheva, 1983; Borscheva, 1986). In turn, in the Kungey Alatau Mountains we have a strong influence of big water bodies (the Kolsay lakes), which are located in relative proximity to our sampling site. Such a neighborhood helps trees to tolerate dry periods, making them less dependent on precipitation. However, at the same time it masks climatic signal which is reflected in the low statistical results of the KOL chronologies as well as in clearly observable difference in variation of the TRI, illustrated by the 15-year low-pass filter, compared to other sampling sites. Similar distortions of climatic signal produced by the Lake Bol’shoye Almatinskoye were previously documented in the study by Passmore et al. (2004), in the Ile Alatau Mountains. Comparing our results with results of studies conducted in the Ile Alatau and northern part of the Zhetysu Alatau, we see additional differences in climate-growth relationships. For example, in results presented by Zhang et al. (2017b), TRW of Schrenk spruce showed strongest correlations with current year precipitation and temperature, whereas our samples, collected in the southern part, revealed the highest correlation with climatic conditions of previous year data. Also, all our chronologies showed the strongest correlations with precipitation data and SPEI03, whereas in results presented by Zubairov et al. (2018b) and Zhang et al. (2017b), strongest correlations were revealed with temperature data. Such differences in climate-growth relationships could be associated with reduction of precipitation from West to East, because our study areas are more closed for entrance of northern and northwestern air masses compared to the Ile Alatau and northern part of the Zhetysu Alatau Mountains (Aizen et al., 1997; Bolch, 2007). Stronger correlations with the SPEI03 and precipitation compared to temperature is also in agreement with recent results published by Babst et al. (2019), who revealed a probability that precipitation exceeded temperature as the main driver of tree growth in temperate and boreal forest biomes.

Extreme years and periodicities showed high agreement with results obtained in earlier studies conducted in the northern Tien Shan Mountains. In particular, the periodicities of ~2-4, 7, 11 and 50-60 years were previously noted in the studies by Borscheva (1983; 1986), Chen et al. (2017), Zhang et al. (2017a; 2017b) and Panyushkina et al. (2018). These periodicities could be associated with the North Atlantic Oscillation (NAO) (Telesca et al., 2013; Gerlitz et al., 2016), El Niño-Southern Oscillation (ENSO) (Allan et al., 1996), Siberian High index (D'Arrigo et al., 2005), Tropospheric Biennial Oscillations (TBO) (Meehl, 1987), East Asian Winter Monsoon (EAWM) (Jhun and Lee, 2004) and the solar activity (Rind, 2002). In turn, revealed extreme positive and negative years (± 2σ) occurred in 1879, 1885, 1897, 1917, 1927, 1951 and 2008, were also previously detected in the studies by Zhang et al. (2017a; 2017b), Passmore et al. (2004), Panyushkina et al. (2018) and Zubairov et al. (2018a). In addition to those extreme years we revealed 13 new ones: in 1882, 1894, 1932, 1941 and 1946 at the KOL, in 1890, 1900, 1925, 1937 and 1959 at the BKP and in 1951, 1955, and 1975 at the TSK sites.

The results of the spatial correlation analysis also revealed some differences between our chronologies. Spatial correlations with the LW cover a smaller area and have lower correlation values compared to the EW and the TRW, which is probably because of the shorter period of the LW formation. In general, the LW formation is driven by hydro-thermal conditions in June-July, June-August, whereas the period of EW formation is mostly driven by hydro-thermal conditions from the previous autumn to current spring (Borscheva, 1983; Borscheva, 1986; Zubairov et al., 2018b). Therefore, the LW growth probably mainly reflects changes in weather conditions confined to a certain territory within relatively short time.

One of our most interesting findings was the reduction of correlations with temperature during the last 50-70 at all our study sites. The same signal was also previously noted in the Ile Alatau Mountains (Zubairov et al., 2018b) and it can be associated with the changes in the structure of temperature signal in radial tree growth since the middle 20th century, also known as "Divergence Problem" (D'Arrigo et al., 2008). At the same time, we see increasing correlation with precipitation and drought index. It appears that despite the general warming-wetting trend, increase in temperature is not compensated by increase in precipitation. Similar changes in climate-growth relationships probably can be found with other tree species as well. For example, according to Panyushkina et al. (2017) almost at the same time, after ca. 1970 and in the same region, wild apple (Malus sieversii [Ldb.] M. Roem) showed a shifting of TRW variability response from temperature to moisture, which was associated with unprecedented intensified Arctic Oscillations and correspondent changes in winter – spring climatic conditions. Such strong influence of climate warming causes certain concerns, because it can probably have a negative effect on the regeneration of Schrenk spruce. Moreover, the possibility of such an effect was previously found with another coniferous species, the Siberian Larch (Larix sibirica) in a study by Dulamsuren et al. (2013) in the mountains of eastern Kazakhstan.

5 Conclusion

We examined the variability of climate-growth relationships of Schrenk spruce in the Ile River basin (northern Tien Shan Mountains). Our results show a high degree of consistency with earlier studies, additionally revealing certain differences reflected in variation of extreme years, periodicities and value of climatic parameters for Schrenk spruce growth in different parts of the basin. Understanding these features in turn is very important for projecting possible environmental changes connected with climate change impact. Our results show decreasing temperature signals, accompanied by increased correlations with precipitation and drought index starting from 1960s – 1980s, which appears to be the result of the regional warming-wetting trend. A new ~2-3, 2-4 high-frequency cycles were revealed in the latewood and earlywood chronologies from the Terskey Alatau Mountains. In turn, our samples from the Kungey Alatau Mountains revealed strong distortions of climatic signal connected with the influence of the Kolsay lakes. Analysis of variations in tree-ring indices, revealed certain extreme years occurred in 1879, 1882, 1890, 1894, 1900, 1925, 1932, 1937, 1941, 1946, 1951, 1955, 1959 and 1975. We also revealed differences in the influence of climatic conditions of the previous and current years. Providing new information on climate-growth relationships of Schrenk spruce, this study contributes to the development of tree-ring network of the Central Asia and helps to disentangle complex climate-growth relationships of the dominant tree species in the northern Tien Shan Mountains. Of course, revealed information need to be further studies and supported by new data. Therefore, further efforts should be taken to develop more spatially extensive and longer tree-ring chronologies. Finally, implementation of new methods, like wood anatomy and stable isotope analysis, should complement ring width analyses and provide additional climatic information.

Acknowledgements

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Supplementary Material

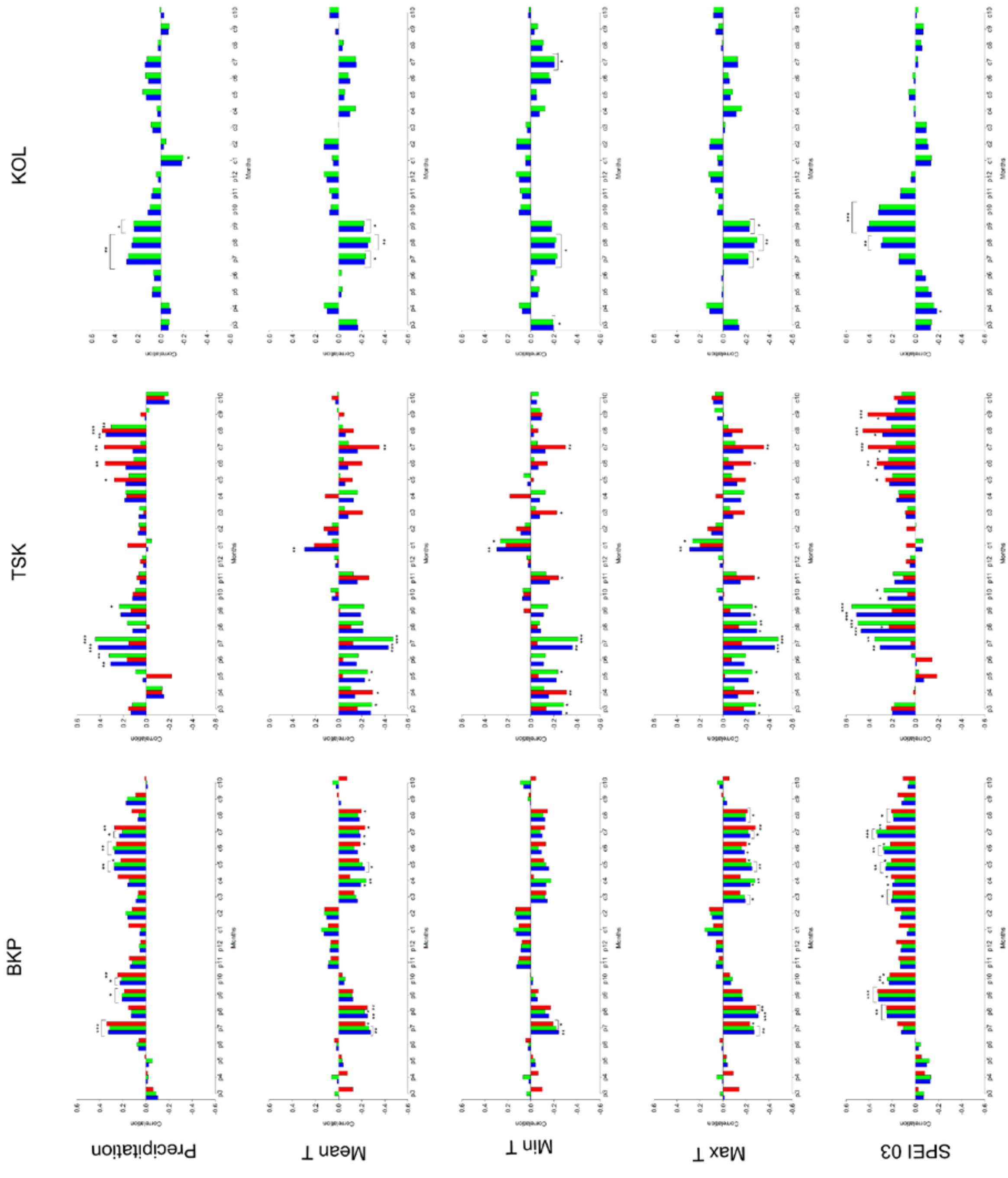

Figure SM IV-1: Correlations between the TRI and climate data (1901-2017) from previous March to current October. MaxT, MinT and MeanT, stands for mean maximum, mean minimum and mean temperature, SPEI03 – stands for 3-month SPEI, which is a difference between potential evapotranspiration and precipitation accumulated over the 3 months before to the current month. Green, blue and red color stands for EW, TRW and LW respectively. *(p<0.05), **(p<0.01), ***(p<0.001).

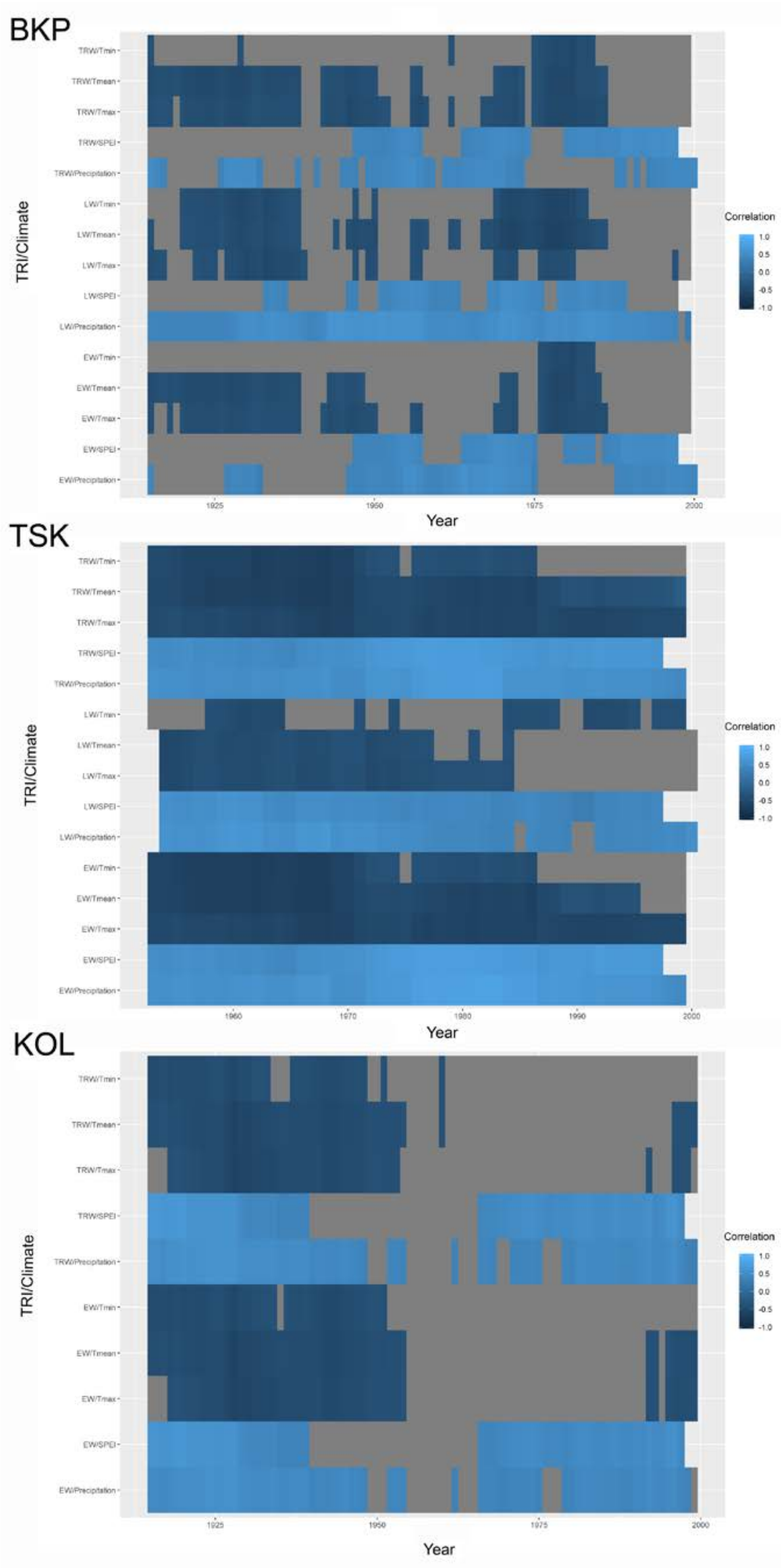

Figure SM IV-2: The running correlation analysis between the chronologies and climate data (window size = 31 years, minimum number of years with data = 1). All correlations are statistically significant (*p*<0.05).

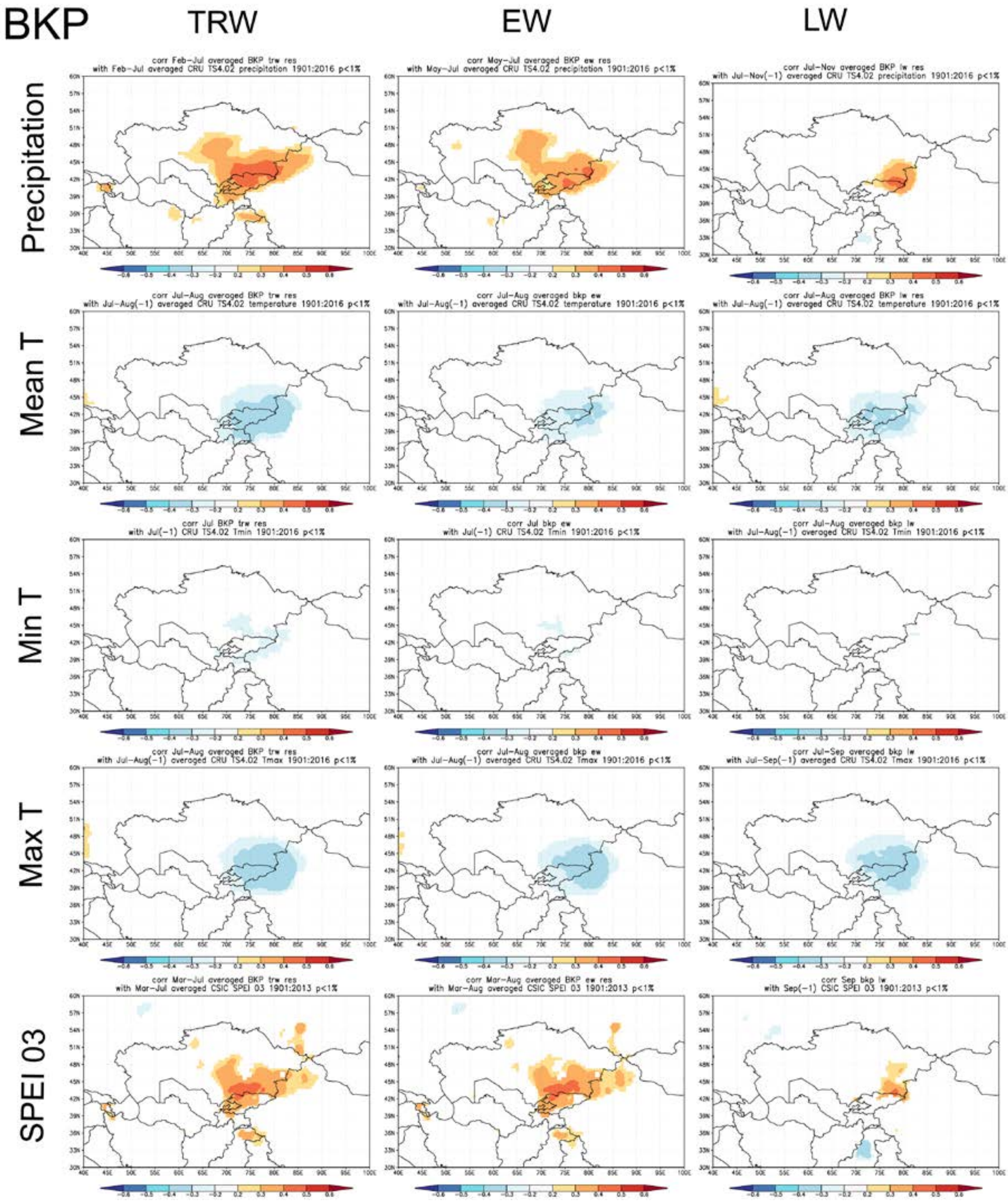

Figure SM IV-3: Spatial correlations between the BKP chronologies and CRU TS 4.02 climate data (1901-2016, *p*<0.01).

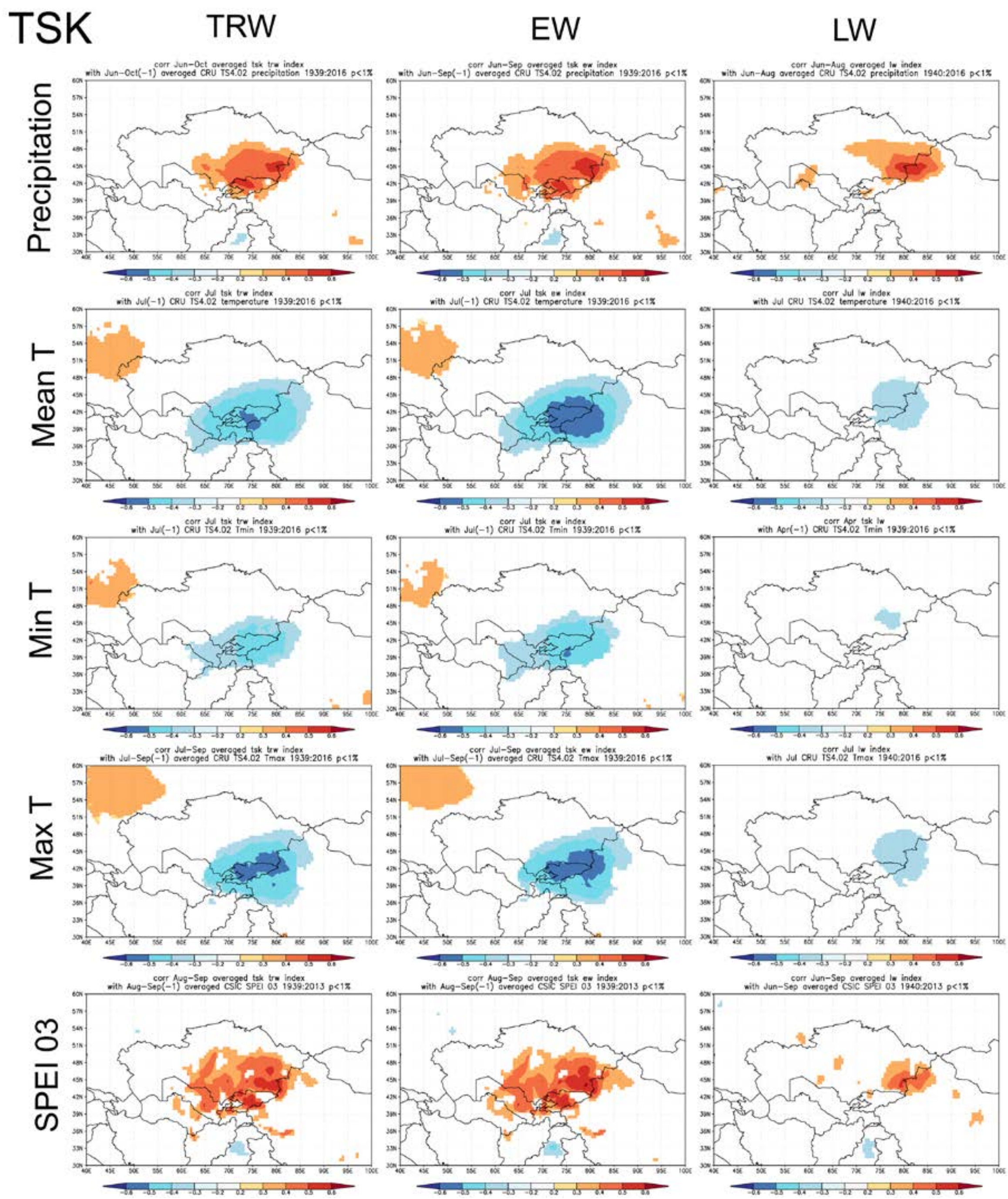

Figure SM IV-4: Spatial correlations between the TSK chronologies and CRU TS 4.02 climate data (1901-2016, p<0.01).

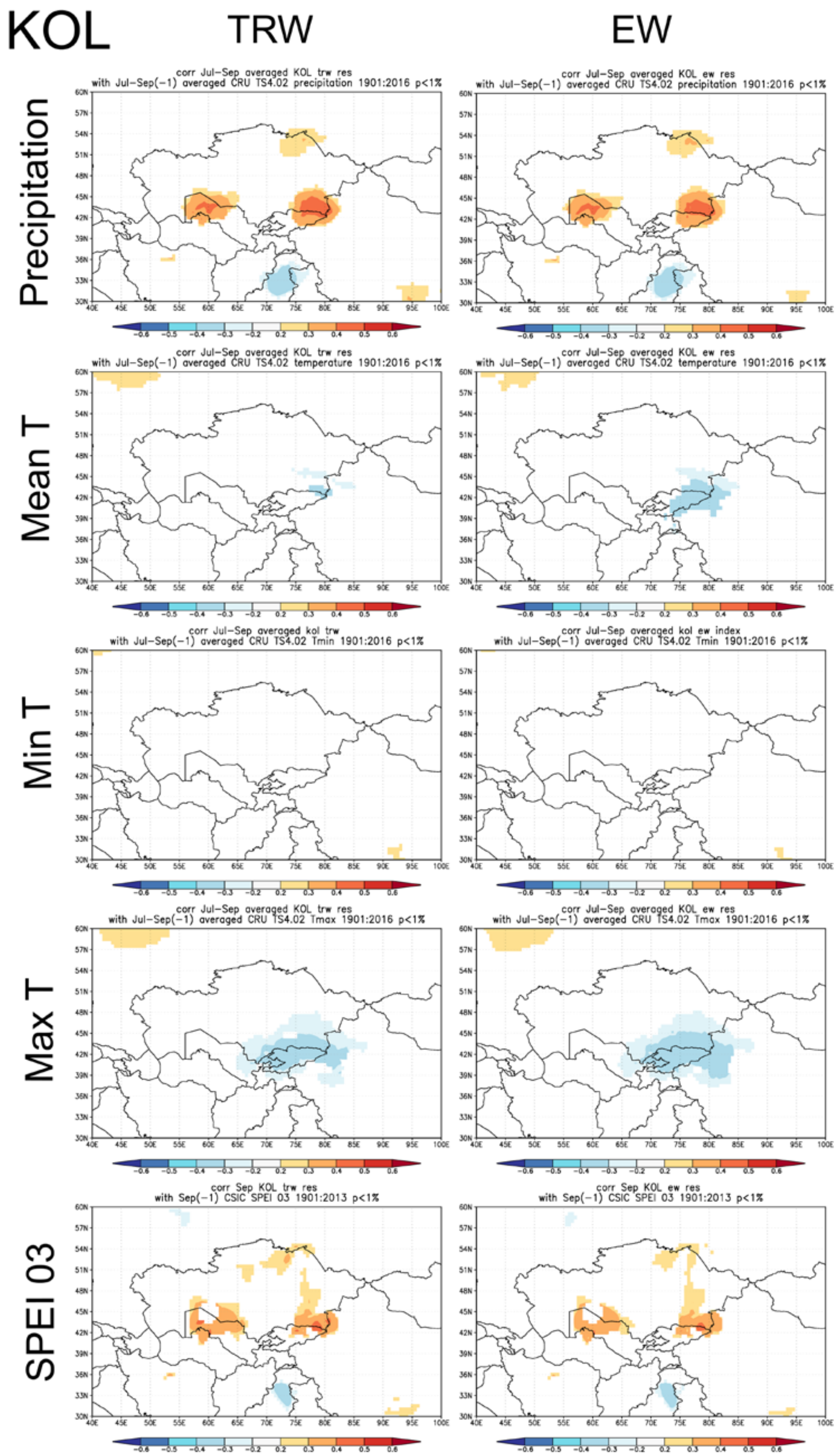

Figure SM IV-5: Spatial correlations between the KOL chronologies and CRU TS 4.02 climate data (1901-2016, *p*<0.01).

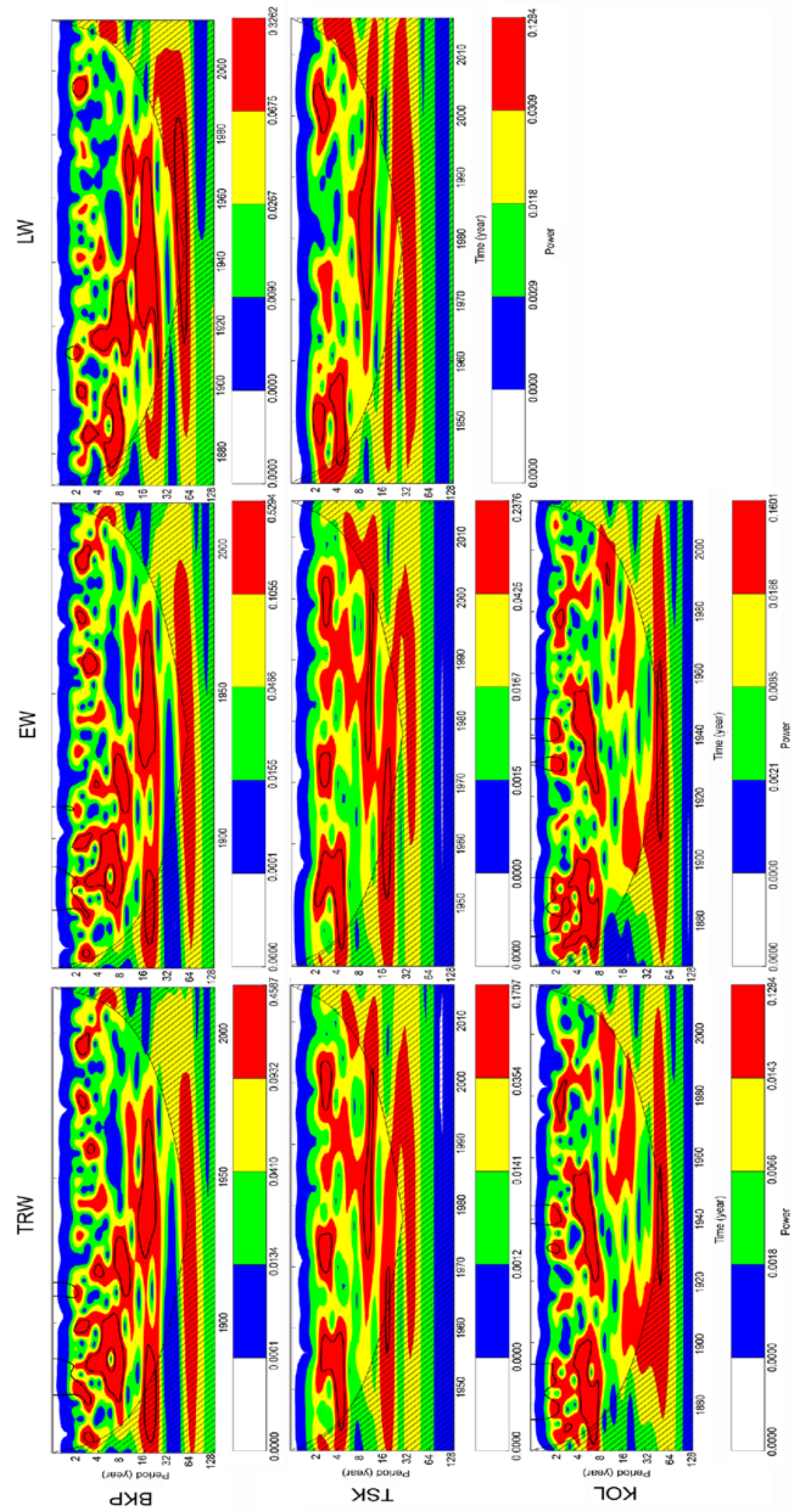

Figure SM IV-6: The wavelet power spectrum. The contour levels were chosen so that 75, 50, 25 and 5% is above each level respectively. The black contour is the 10% significance level with a red-noise (autoregressive lag-1) background spectrum.

Chapter V:
Synthesis

1 Summary

The overarching goal of this thesis was to gain a better understanding of climate-growth relationships of Schrenk spruce in the Ile River basin and possible changes in these relationships due to climate change. The Schrenk spruce was and remains the most frequently used tree species for dendroclimatic studies in Kazakhstan. Thanks to thorough studies by Borscheva (1983; 1986) and a number of recent studies by Passmore et al. (2004), Chen et al., (2017), Zhang et al. (2018), Panyushkina et al. (2018) and others, we already know a lot about the reaction of Schrenk spruce growth to climate variation. Nevertheless, certain research gaps which limit our knowledge still exist. Addressing these gaps is an important issue, especially when taking into account the strong negative impact of climate change. These impacts have already been observed in forests of eastern Kazakhstan, where growth and regeneration of Siberian larch was affected so strongly that in the near future timber harvest may not be possible there (Dulamsuren et al., 2013). The social and economic influence of such negative events is very strong. In the Ile River basin it is probably even stronger than in other parts of Kazakhstan, because it is the most populated and the most economically developed region.

The concerns regarding a changing climate in the region are amplified due to two facts: the first is additional pressure from phenomena such as overgrazing, overharvesting and other anthropogenic influences. The second is the connection of a forest’s functioning and dynamics with natural hazards such as insect outbreaks, landslides and avalanches. The last two are especially relevant in the Ile River basin, which is surrounded by the Tian Shan Mountains. For effective mitigation and adaptation to possible negative consequences, development of tree-ring networks and new temporally extensive chronologies are of great importance. The generalization and qualitative analysis of already available information supplemented by new chronologies built on Schrenk spruce samples collected in the less studied areas of southeastern Kazakhstan could help to answer the two key research questions asked in this thesis.

<u>Research Question I:</u> *What do we know about climate-growth relationships of Schrenk spruce in Kazakhstan?*

Chapter II focused on qualitative analysis of all available dendroclimatic publications in Kazakhstan. In total, data from 43 dendroclimatic studies and 13 studies related to other subfields of dendrochronology were generalized. This analysis includes studies published in peer-reviewed journals, monographs and graduate works published in Russian, Kazakh, German and Chinese languages. It appeared that dendroclimatic studies in Kazakhstan began in 1970s, and were especially active in the southeastern part of Kazakhstan, mainly investigating climate-growth relationships of Schrenk spruce. According to results presented in a majority of publications, the main limiting factor of growth was found to be the precipitation from the previous autumn to current spring and summer temperatures (Borscheva, 1983; Jurina et al., 2006; Zhang et al., 2017a). Previous year precipitation provides important moistening of the soil for the upcoming growing season which is beneficial for Schrenk spruce growth (Borscheva, 1983; Chen et al., 2017; Zhang et al., 2017a). In turn, high summer temperatures increase evapotranspiration which can affect the production of sugars and be considered as a manifestation of drought stress (LaMarche, 1974). Detected periodicities indicated the influence of the North Atlantic Oscillation, the Tropospheric Biennial Oscillations and the El Niño-Southern Oscillation on variations of tree-ring growth (Chen et al., 2017; Zhang et al., 2017a; Zhang et al., 2017b; Zubairov et al., 2018a; Panyushkina et al., 2018). A number of differences in variations of climate-growth relationships were attributed to certain differences in precipitation regime, orography and the age of trees (Borscheva, 1983). For example, in narrow gorges of Kungey Alatau, Schrenk spruce appeared to be more sensitive to temperature conditions than to precipitation (Borscheva, 1983). In the Terskey Alatau, trees are more sensitive to precipitation compared to the Ile Alatau, which is associated with decreasing amounts of precipitation from West to East (Aizen et al., 1997; Bolch, 2007). Analysis also revealed a necessity of further investigation to generate more spatially extensive and longer tree-ring chronologies, which should help clarify certain climatic features and how they affect tree growth (Chen et al., 2017; Zhang et al., 2017b).

Research Question II: How does the response of Schrenk spruce growth on climate variation in the Ile River basin vary spatially and temporally, and how is it associated with climate change?

The comparative analysis from chapter II provided important information on the climate – growth relationships of Schrenk spruce and existing research gaps. In chapter III we addressed one of these gaps by investigating which tree-ring parameter and which climate data provide best correlation results for different age groups of trees. The importance of this study was highlighted by the fact that the last time similar investigations were conducted was more than 30 years ago by Borscheva (1983; 1986). In general our results were in agreement with results provided by Borscheva: latewood (LW) showed strongest correlations with temperature and earlywood (EW) with precipitation. The total ring width (TRW) demonstrated strongest correlations with the Standardized Precipitation-Evapotranspiration Index (SPEI) which was in agreement with results presented by Chen et al. (2017). At the same time, application of separate analysis for different age groups of trees as well as use of daily climate data improved our results, providing better correlation values and more precise time intervals. One of the most interesting findings was a reduction of temperature signal starting from 1979 which was also reflected in the weak statistical results of the LW chronology. This could be the direct influence of climate warming and is probably associated with a reduction of Schrenk spruce mean sensitivity and changes in the structure of temperature signal due to so called “Divergence Problem” (D’Arrigo et al., 2008).

Reduction of the temperature signal was also revealed in other parts of southeastern Kazakhstan, in particular in the Kungey Alatau, the southern Zhetysu Alatau and the Terskey Alatau, as was shown in chapter IV. At the same time, this reduction was accompanied by increased correlations with precipitation and the SPEI drought index. Developed chronologies revealed certain differences in extreme years and periodicities. For LW and EW, chronologies from the Terskey Alatau revealed new high-frequency cycles. Climate-growth relationships showed certain spatial and temporal variations due to differences in humidification conditions and orography. Additionally, a strong influence on climatic signal was revealed in the Kungey Alatau due to the proximity of the Kolasay lakes. In particular, a difference was revealed in the reaction to previous and current year climate conditions. It appeared that in the southern Zhetysu Alatau, LW growth is primarily driven by current year climatic conditions and EW and TRW are driven by conditions in the previous year, whereas in the Terskey Alatau growth of all parameters are relatively equally influenced by both previous and current year climate conditions. Additionally, dryer conditions in the southern part of the Zhetysu Alatau are resulted in stronger correlations with precipitation and the SPEI drought index.

2 Main conclusions and implications

2.1 Main conclusions

Together the results of the core chapters contributed to reaching the overarching goals of this thesis. The main insights from the chapters II-IV foster understanding the variations of climate-growth relationships of Shcrenk spruce in the Ile River basin. Chapter II indicated the necessity of developing the tree-ring network of Kazakhstan, and demonstrated the great importance of early studies for understanding the dynamics and interconnections between climate and Schrenk spruce growth. The data scarcity and the existence of research gaps appeared due to the break in dendroclimatic investigations associated with the collapse of the Soviet Union. This break resulted in a relatively small time period of existing tree-ring chronologies and strong spatial heterogeneity of conducted dendroclimatic studies. As a result, some areas such as Zhetysu Alatau, the Kungey Alatau and the Terskey Alatau turned out to be practically unexplored.

Detailed dendroclimatic studies in these regions are further complicated by the availability of climate data. Daily climate data from meteorological stations could provide the best results, but unfortunately, very often availability and completeness of these datasets is insufficient, which significantly limits their usage. In turn gridded climate data, for example Climate Research Unit (CRU) (Harris et al., 2014), provide a good alternative. However, with such data we often have more coarse temporal resolution (monthly instead of daily) and also can face some other effects like shifting of periods of strongest correlations between climate and tree-ring growth, which can result in wrong conclusions.

Comparative analysis revealed certain consistency with previous studies indicating strong positive influence of precipitation from previous autumn to current spring (Borscheva, 1983; Chen et al., 2017; Zhang et al., 2017a). Circulation of northern and northwestern air masses coupled with orography appeared to play a very large role in the period of formation of earlywood and latewood of Schrenk spruce in the Ile River basin. Certain periodicities detected in variation of tree-ring growth implied an influence of the North Atlantic Oscillation (NAO) (Telesca et al., 2013; Gerlitz et al., 2016), Siberian High index (D'Arrigo et al., 2005), Tropospheric Biennial Oscillations (TBO) (Meehl, 1987), El Niño-Southern Oscillation (ENSO) (Allan et al., 1996), the solar activity (Rind, 2002) and East Asian Winter Monsoon (EAWM) (Jhun and Lee, 2004). The combination of data from the chapters III and IV provided new information on features of climate-growth relationships across the entire Ile River basin. Those features are reflected in the differences and similarities of extreme years, periodicities and value of climatic parameters for Schrenk spruce growth in different parts of the basin (Figure V-1). Understanding these features in turn is very important for projecting possible environmental changes connected with climate change impact.

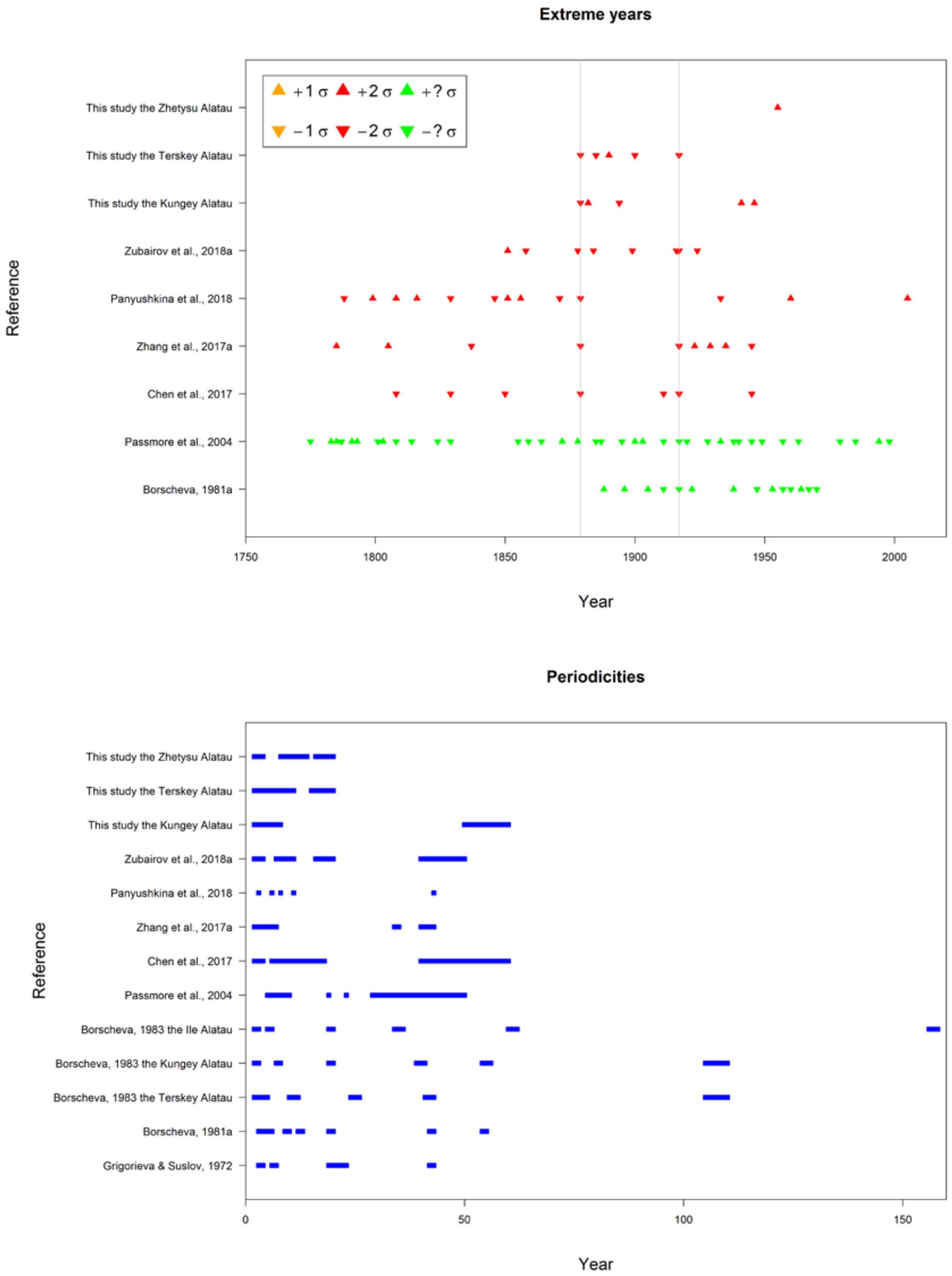

Figure V-1: Comparative plot of revealed extreme years and periodicities. Grey lines indicate common extreme years. Color and position of triangles indicate the sign and degree of deviation of values in the corresponding year.

One of the consequences of climate change impact detected in the Ile River basin is the reduction of the temperature signal in the tree rings of Schrenk spruce starting from 1960s – 1980s depending on the part of the basin, and the increase of precipitation and drought signals. The difference of around 20 years in reaction again illustrated the complexity of climate-growth relationships of Schrenk spruce and necessity of developing the tree-ring network. While in one part of the basin we have an amplified response, in the other part the effect of climate change is mitigated by certain local environmental features. Some regions, for example southern Zhetysu Alatau, appeared to be more vulnerable because of dryer conditions. Alternatively, in the Ile Alatau where the amount of precipitation is higher, the effect of high temperatures is not so pronounced. Nevertheless, despite certain differences in strength and scale of response, changes affect the entire Ile River basin. According to analysis presented in the National Strategy and Action Plan on Sustainable Development of Kazakhstan Mountain Territories, during the period 1964-1984 a steady reduction in the area of forests and shrubs and the renewal of coniferous forests was revealed. For example during the period 1960-1990 the wild apple habitat reduced by 30% in the Zhetysu Alatau and by 60% in the Ile Alatau (National Academy of Sciences of the Republic of Kazakhstan, 2001). At the same time, the fact that the data are given for sparsely populated areas indicates low anthropogenic influence and high value of climatic factors.

For a more accurate assessment of changes in the functioning and dynamics of Schrenk spruce forests in the Ile River basin and for better understanding of possible future effects, additional information is of high importance. Therefore, new extensive dendroclimatic studies are required.

2.2 Implications

The results of this dissertation may find applications in a wide variety of tasks. Forest resource managers, local authorities, National Parks administration and the Forestry and Wildlife Committee at the Ministry of Agriculture of the Republic of Kazakhstan may potentially use obtained data for planning programs for conservation and restoration of forests, for developing policies for sustainable forest resource use as well as for taking measures aimed at mitigating and adapting forestry to the possible negative effects of climate change.

The information from the chapter II could be very helpful in further dendroclimatological and dendroecological studies conducted in Kazakhstan and in adjacent territories. In particular, the analysis provided in this chapter can help researchers to understand where to focus their efforts, where the lack of information is most strongly felt, which areas are the least explored, and what should be paid attention to when planning a study and allocating time and human resources. Additionally, combined information may be useful for understanding interconnections between different hydrological, climatological, glaciological and geomorphological factors and how they are connected with Schrenk spruce growth in the Ile River basin.

The chapters III and IV, provide new information on climate-growth relationships of Schrenk spruce, contributes to the development of tree-ring network of Kazakhstan. Being uploaded to the International Tree-Ring Data Bank this information could become a small contribution for big and extensive studies aimed to understand global patterns in reaction of tree growth on climate. To some extent, the results of this dissertation could be applied in the process of solving certain issues stated in the National Strategy "Kazakhstan – 2050" and in solving several challenges that are mentioned in this strategy, including exhaustion of natural resources, severe water shortage and food insecurity (http://www.akorda.kz/ru/official_documents/strategies_and_programs).

These results could also be helpful for implementation of projects developed under the conventions and declarations ratified by Kazakhstan aimed at preserving biodiversity and adaptation to climate change. At the regional and country level, these results can be applied to address a number of issues specified in the National Strategy and Action Plan on Sustainable Development of Kazakhstan Mountain Territories. Here just few of them: monitoring of status of components of biodiversity, complete biodiversity accounting and assessment of their dynamic state, development of regulatory frameworks and measures for the conservation and rational use of forest ecosystems and its components, which also connected with a lack of information on the state of soil and plant resources in mountain areas (National Academy of Sciences of the Republic of Kazakhstan, 2001).

In Kazakhstan about 300, 000 people depend directly on the forest sector, and indirectly up to 4-5 million people use forest resources for their livelihood (Meshkov et al., 2009; Sehring, 2012). People use forest for fuel wood and cattle forage, for herb collecting, hunting, recreation and many other needs. All these activities put constant pressure on forest ecosystems, and this pressure is not spatially even. Information obtained in this dissertation could be applied by forest managers in regulation processes to strengthen the observation for the most vulnerable areas, building routes for ecotourism and to adjust the afforestation and reforestation measures.

3 Outlook

This dissertation advanced understanding of climate-growth relationships of Schrenk spruce in the Ile River basin. A qualitative synthesis of available publications supplemented by new data was presented. Samples were collected at three of the least studied areas of the Ile River basin, and a first analysis between daily climate data and different tree-ring parameters was performed. Characteristics and features of the reaction of Schrenk spruce growth with climate were identified. These characteristics can help to fill some of the gaps in our understanding of Schrenk spruce forest dynamics and functioning in the Ile River basin. Nevertheless there are still many open research questions remaining. First of all, the number of studies in the Zhetysu Alatau, the Terskey Alatau and the Kungey Alatau is still very low.

The total number of studies conducted in these three mountain ranges is less than those that were carried out in the Ile Alatau. Secondly, the majority of studies were conducted in the lower forest belt, whereas climate-growth relationships near the upper tree line are still rather poorly understood. This is especially relevant due to projected climate change and vulnerability of high mountain areas (Garcia et al., 2014; Mountain Research Initiative EDW Working Group, 2015; Pecl et al., 2017). New and expanding technologies could also provide opportunities to implement new techniques and methods, including stable isotope and wood anatomy analyses.

Currently there are no studies on wood anatomy and only one study on stable isotopes in Kazakhstan: by Zhang et al. (2019). Close cooperation between research groups is needed as well as dendroclimatic studies on an ongoing basis. Joint efforts and systematic observations will significantly improve quality of studies and also contribute to a deeper understanding of climate-growth relationships. Special attention should be paid to the study of unique ecosystems, such as Chin-Turgen, where spruce forests grow on the permafrost ground covered by thick layer of moss. Climatic influence on tree growth at such places could be strongly modified by local environmental features. Therefore, forest ecosystem functioning here can be significantly different compared to other areas.

The number of dendroclimatic investigations on other tree species in Kazakhstan, and in the Ile River basin particularly, is also very low. Meanwhile, there is a very good potential for investigation of tree species, e.g., juniper. Forests of the southeastern Kazakhstan consist not only of Schrenk spruce but of many species, including: maple (Acer semenovii), aspen (Populus tremula), birch (Betula pendula), and juniper (Juniperus pseudosabina). These species are an important part of mountain ecosystems, and we should therefore learn more about their climate-growth relationships.

Finally, investigations in other fields of dendrochronology, such as dendroecology, dendrogeomorphology, dendrochemistry, dendroarcheology are of high importance, since they could improve our understanding about climate-environment-society nexus in Kazakhstan.

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Eidesstattliche Erklärung

Hiermit erkläre ich, die vorliegende Dissertation selbstständig und ohne Verwendung unerlaubter Hilfe angefertigt zu haben. Die aus fremden Quellen direkt oder indirekt übernommenen Inhalte sind als solche kenntlich gemacht. Die Dissertation wird erstmalig und nur an der Humboldt-Universität zu Berlin eingereicht. Weiterhin erkläre ich, nicht bereits einen Doktortitel im Fach Geographie zu besitzen. Die dem Verfahren zu Grunde liegende Promotionsordnung ist mir bekannt.

Bulat Zubairov

Berlin, den 12.08.2019